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TESTS OF ROCK CORES, DULUTH-VERMILLION STUDY AREA, MINNESOTA.(U)
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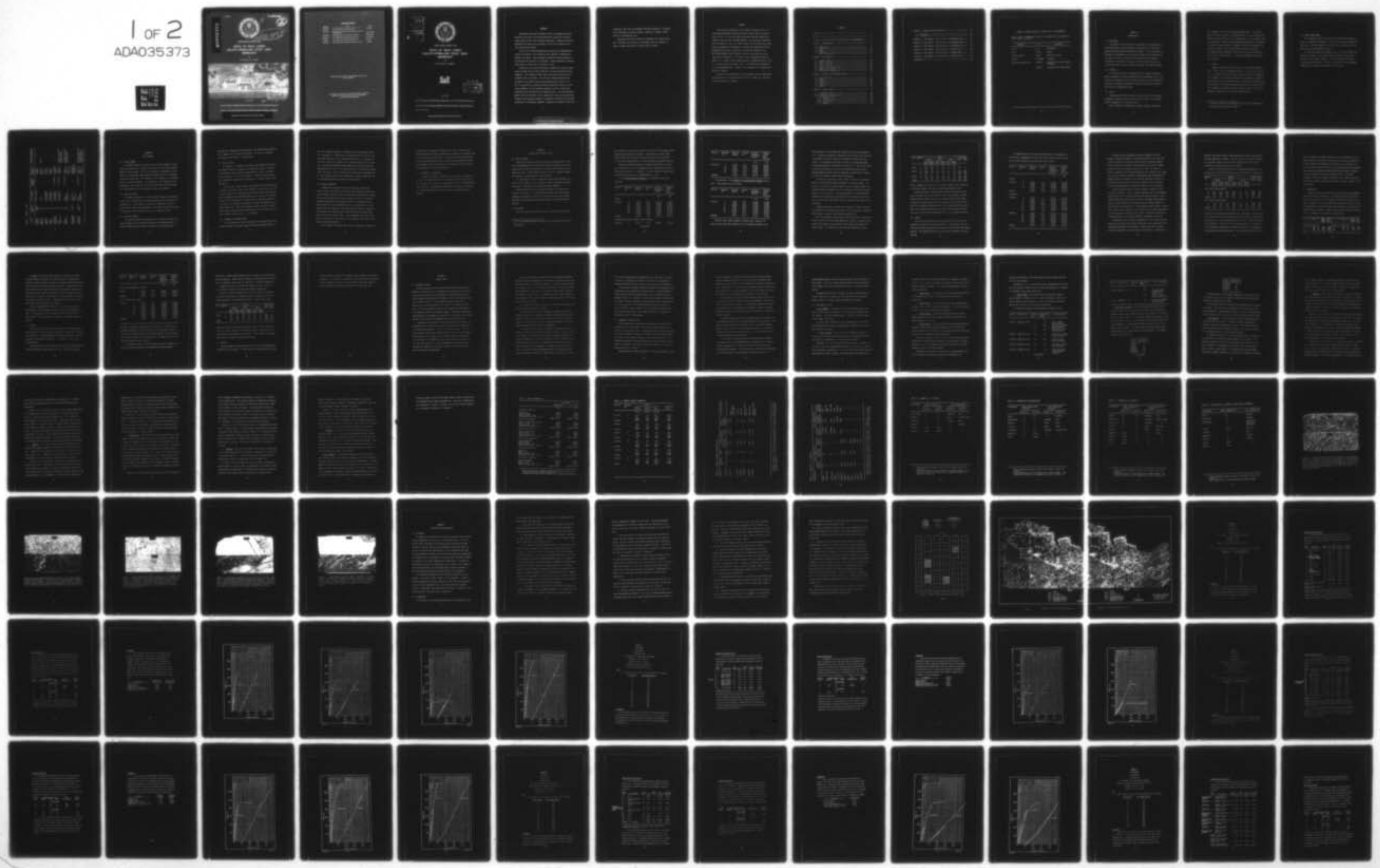

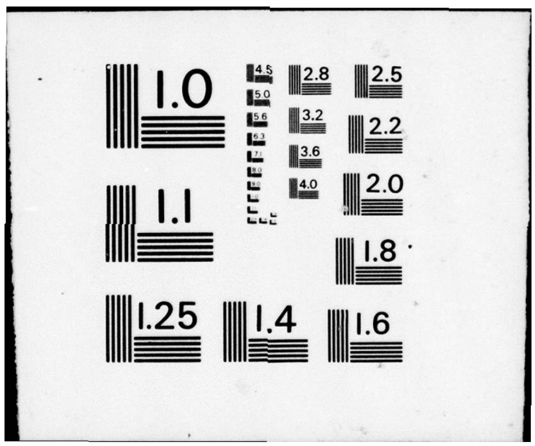
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MISCELLANEOUS PAPER C-70-9

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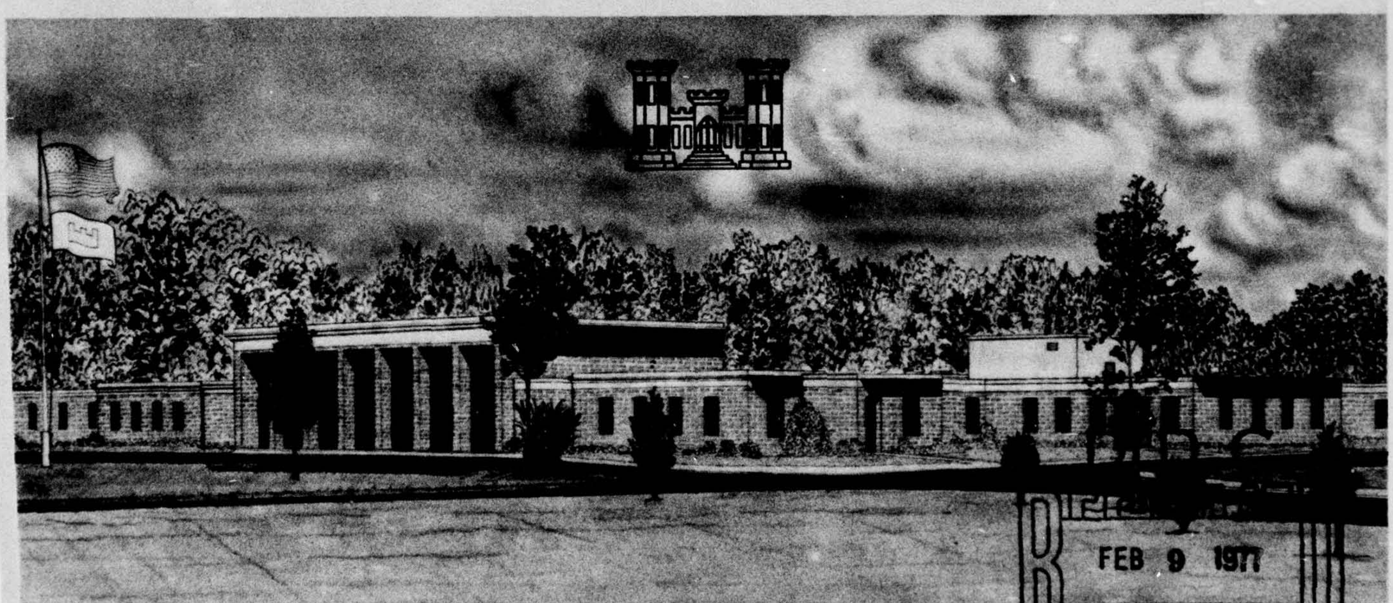

June 1970

Sponsored by Space and Missile Systems Organization, U. S. Air Force Systems Command

Conducted by U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

See 1473

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ASSOCIATED REPORTS

Report No.	Title	Date
MP C-69-3	Tests of Rock Cores, Warren Area, Wyoming	March 1969
MP C-69-12	Tests of Rock Cores, Mountain Home, Idaho, and Fairchild, Washington, Areas	September 1969
MP C-69-16	Tests of Rock Cores, Castle Study Area, California	October 1969
MP C-70-4	Tests of Rock Cores, Bergstrom Study Area, Texas	February 1970
MP C-70-6	Tests of Rock Cores, Scott Study Area, Missouri	May 1970
MP C-70-7	Tests of Rock Cores, Plattsburgh Study Area, New York	June 1970

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ARMY-MRC VICKSBURG, MISS.

ABSTRACT

Laboratory tests were conducted on rock core samples received from six core holes in the Duluth-Vermillion study area of Koochiching, Lake, and St. Louis Counties, Minnesota. Results were used to determine the quality and uniformity of the rock to depths of 200 feet below ground surface.

The rock core was petrographically identified as predominantly tonalite and gabbro, with relatively minor amounts of amphibolite, granite, and gneiss. Many specimens contained fractures ranging in orientation from vertical to horizontal. Several specimens contained bands and/or contacts with other types of rock.

Evaluation on a hole-to-hole basis indicates the tonalite represented by specimens from Hole DV-CR-19 to be quite uniform and very competent. This material should offer very good possibilities as a competent hard rock medium. The tonalite, medium-grained gabbro, and granite and granitic gneiss representing Holes DV-CR-17, -40, and -9, respectively, exhibited physical properties typical of relatively competent to very competent material, and all should offer reasonably good possibilities as competent media. The coarse-grained gabbro from Hole DV-CR-24, and the amphibolite and tonalite from Hole DV-CR-39, were generally marginal (compressive strength 8,000 through 12,000 psi) to relatively competent (compressive strength >12,000 psi)

in quality, with only one specimen (DV-CR-39, Specimen 7, an amphibolite) yielding an ultimate uniaxial compressive strength characteristic of incompetent rock.

Evaluations have been confined to specimens from single holes and, therefore, more extensive investigation will be required in order to expand evaluations to entire areas of media.

PREFACE

This study was conducted in the Concrete Division of the U. S. Army Engineer Waterways Experiment Station (WES) under the sponsorship of the U. S. Air Force Space and Missile Systems Organization (SAMSO) of the Air Force Systems Command. The study was coordinated with CPT Rupert G. Tart, Jr., SAMSO Project Officer, Norton Air Force Base, San Bernardino, California. The work was accomplished during September and October of 1969 under the general supervision of Mr. Bryant Mather, Chief, Concrete Division, and under the direct supervision of Messrs. J. M. Polatty, Chief, Engineering Mechanics Branch, W. O. Tynes, Chief, Concrete and Rock Properties Section, and K. L. Saucier, Project Officer. Mr. C. R. Hallford was responsible for the petrography work. Messrs. R. W. Crisp and K. L. Saucier prepared this report.

Director of the WES during the investigation and the preparation and publication of this report was COL Levi A. Brown, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows.

Multiply	By	To Obtain
inches	25.4	millimeters
feet	0.3048	meters
feet per second	0.3048	meters per second
pounds	0.45359237	kilograms
pounds per square inch	0.070307	kilograms (force) per square centimeter
	6.894757	kilonewtons per square meter

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The purpose of this study was to supplement the information being obtained for the area evaluation study by the U. S. Air Force Space and Missile Systems Organization (SAMSO). It was necessary to determine the properties of the specific materials for evaluation of the area as a hard rock medium and, as necessary, for design of structures in the medium. Results of tests on cores from Koochiching, Lake, and St. Louis Counties, Minnesota, are reported herein.

1.2 OBJECTIVE

The objective of this investigation was to conduct laboratory tests on samples from areas containing hard, near-surface rock to determine the integrity and the mechanical behavior of the materials as completely as possible, analyze the data thus obtained, and report the results to appropriate users.

1.3 SCOPE

Laboratory tests were conducted as indicated in the following paragraph on samples received from the field. Table 1.1 gives pertinent information on the various tests.

Tests conducted to determine the general quality, uniformity,

and integrity of the rock in the area sampled were: (1) relative hardness (Schmidt number), (2) specific gravity, (3) unconfined compression (conventional and cyclic compression), and (4) dynamic elastic properties. Special tests conducted, respectively, to determine the degree of anisotropy of the sampled rock and to facilitate comparison of results of direct and indirect tensile tests were: (1) dynamic elastic properties along three mutually perpendicular axes and (2) tensile strength. A limited petrographic examination was also made.

1.4 SAMPLES

Samples were received from six holes in the Duluth-Vermillion area. These holes were designated DV-CR-9, -17, -19, -24, -39, and -40. All samples were NX size cores (nominal 2-1/8-inch[1] diameter). Test specimens of the required dimensions as presented in Table 1.1 were prepared for the individual tests. Quality and uniformity tests were conducted on selected specimens from all holes. Special tests were conducted on specimens selected from the various core holes to represent differences in rock type, weathering, etc.

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[1] A table of factors for converting British units of measurement to metric units is presented on page 8.

1.5 REPORT REQUIREMENTS

The immediate need for the test results required that data reports be compiled and forwarded to the users as work was completed on each hole. The data reports of the individual test results are included herein as Appendixes A through F.

The core descriptions originally given in the data reports (Appendixes A through F) were frequently taken from the core logs received with the sample shipments. These descriptions have been changed, where necessary, to reflect the results of the petrographic examination and analysis performed at a later date.

TABLE 1.1 SUMMARY OF TESTS

Test	Specimen Size	Test Equipment	Recording Equipment	Measured Properties	Computed Properties
Relative hardness	1 diam by 2 diam	Schmidt hammer	--	Relative hardness	--
Specific gravity		Scales	--	Specific gravity	Density
Indirect tension		440,000-pound test machine	--	Tensile strength	--
Direct tension		30,000-pound test machine	--	Tensile strength	--
Unconfined compression		440,000-pound test machine	X-Y recorder	Compressive strength	--
Cyclic compression		440,000-pound test machine	X-Y recorder	Compressive strength	Young's, shear, and bulk moduli and Poisson's ratio
Elastic properties		Pulse generator, amplifiers	Oscilloscope	Compres-sional and shear velocities	Young's, shear, and bulk moduli and Poisson's ratio
Petrographic examination	Variable	Microscopes, X-ray diffraction	--	Appearance, texture, and mineralogy	--
Anisotropy properties	1 diam by 1 diam	Pulse generator, amplifiers	Oscilloscope	Compres-sional and shear velocities	Young's, shear, and bulk moduli and Poisson's ratio in three directions

CHAPTER 2

TEST METHODS

2.1 SCHMIDT NUMBER

The Schmidt number is a measure of the relative degree of hardness as determined by the degree of rebound of a small mass propelled against a test surface. The test was conducted as suggested in Reference 1 (a Swiss-made hammer was used) except that 8 to 12 readings per specimen were made. The average of these readings is the Schmidt number or relative hardness. The hardness is often taken as an approximation of rock quality, and may be correlated with other physical characteristics such as strength, density, and modulus.

2.2 SPECIFIC GRAVITY

The specific gravity of the "as-received" samples was determined by the loss of weight method conducted according to method CRD-C 107 (Reference 2). A pycnometer is utilized to determine the loss of weight of the sample upon submergence. The specific gravity is equal to the weight in air divided by the loss of weight in water.

2.3 INDIRECT TENSION

The tensile strength was determined by the indirect method, commonly referred to as the tensile splitting or Brazilian method, in which a tensile failure stress is induced in a cylindrical test

specimen by a compressive force applied on two diametrically opposite line elements of the cylindrical surface. The test was conducted according to method CRD-C 77 (Reference 2).

2.4 DIRECT TENSION

For purposes of comparison, specimens were prepared and tested for tensile strength according to the American Society for Testing and Materials (ASTM) proposed "Standard Method of Test for Direct Tensile Strength of Rock Core Specimens." Tensile splitting tests were conducted on specimens cut adjacent to the direct tensile test specimens.

For the direct tension tests, the specimens were right circular cylinders, the sides of which were straight to within 0.01 inch over the full length of the specimen and the ends of which were parallel and not departing from perpendicularity to the axis of the specimen by more than 0.25 degree. Cylindrical metal caps were cemented to the ends of the specimen and provided the means for applying the direct tensile load. The load was applied continuously by a 30,000-pound-capacity universal testing machine and at a constant rate such that failure occurred within 5 to 15 minutes.

2.5 COMPRESSIVE STRENGTH TESTS

The unconfined and cyclic compression test specimens were prepared according to ASTM and Corps of Engineers standard method of

test for triaxial strength of undrained rock core specimens, CRD-C 147 (Reference 2). Essentially, the specimens were cut with a diamond blade saw, and the cut surfaces were ground to a tolerance of 0.001 inch across any diameter with a surface grinder prior to testing. Electrical resistance strain gages were utilized for strain measurements, two each in the axial (vertical) and horizontal (diametral) directions. Static Young's, bulk, shear, and constrained moduli were computed from strain measurements. Stress was applied with a 440,000-pound-capacity universal testing machine.

2.6 DYNAMIC PROPERTIES

Compressional and shear wave velocities, bulk, shear, and Young's moduli, and Poisson's ratio were determined by the ASTM proposed "Standard Method of Test for Laboratory Determination of Ultrasonic Pulse Velocities and Elastic Constants of Rock." The method consisted essentially of generating a wave in the specimen with a pulse generator unit and measuring, with an oscilloscope, the time required for the compression and shear waves to travel the length of the specimen, the resulting wave velocity being the distance traveled divided by the travel time. These compressive and shear velocities, along with the bulk density of the specimen, were used to compute the elastic properties.

In the case of the special tests used to determine the degree of

anisotropy of the samples, compression and shear velocities were measured along two mutually perpendicular, diametrical (lateral) axes and along the longitudinal axis. This was facilitated by grinding four 1/2-inch-wide strips down the sides of the cylindrical surface at 90-degree angles and generating the compressive and shear waves perpendicular to these ground surfaces.

2.7 PETROGRAPHIC EXAMINATION

A limited petrographic examination was conducted on samples selected to be representative of the material from the several holes. The examination was limited to identifying the rock, determining general condition, identifying mineralogical constituents, and noting any unusual characteristics which may have influenced the test results.

CHAPTER 3

QUALITY AND UNIFORMITY TESTS

3.1 TESTS UTILIZED

Experience accumulated through testing and data analysis of core from study areas previously evaluated[1] dictated selection of the following tests for use in determining the quality and uniformity of the Vermillion core: Schmidt number, specific gravity, uniaxial compressive strength, and compressional wave velocity.

The core received from the Vermillion study area generally consisted of five types of rock: tonalite, gabbro, amphibolite, gneiss, and granite. The gabbro and tonalite were most abundant.

Physical test results were generally grouped and analyzed according to rock type. In most instances, however, the data further suggested and reflected subdivision according to grain size, nature and degree of fracturing, and nature and degree of foliation and/or banding.

3.2 TONALITE

The rock core received from two entire holes (DV-CR-17 and -19)

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[1] A list of associated reports is given on the inside front cover of this report.

and portions of that received from a third hole (DV-CR-39) were petrographically identified as tonalite. The tonalites received from Holes DV-CR-17 and -39 were coarse grained while those from Hole DV-CR-19 were medium grained. Several specimens contained fractures.

Physical properties appeared to depend predominantly on grain size, since most of the core appeared intact (macroscopically free of fractures and joints). A summary of the test results is given below. Detailed results are given in Appendixes B, C, and E.

For the <u>medium-grained tonalite</u>, the following results were obtained:

Hole No.	Specimen No.	Specific Gravity	Schmidt No.	Ultimate Compressive Strength	Compressional Wave Velocity
				psi	fps
Intact:					
DV-CR-19	2	2.639	49.7	34,390	16,970
	8	2.643	53.5	32,580	17,230
	11	2.638	49.2	36,520	16,020
	12	2.640	53.1	36,140	16,530
	15	2.648	53.1	36,210	16,760
	18	2.656	49.8	40,300	16,110
	21	2.639	50.0	35,610	16,140
Average		2.643	51.2	35,960	16,540
Containing Fractures, Bands, and/or Contacts:					
DV-CR-19	5	2.647	50.1	23,940	16,330

(Continued)

Hole No.	Specimen No.	Specific Gravity	Schmidt No.	Ultimate Compressive Strength	Compres-sional Wave Velocity
				psi	fps
DV-CR-39	2	2.669	54.0	30,300	18,800
	11	2.727	50.2	15,210	18,670
	15	2.777	50.9	15,030	20,500
	18	2.681	55.2	13,150	19,720
	20	2.658	56.3	24,520	19,150
Average		2.693	52.8	20,360	18,860

All specimens of the medium- to coarse-grained tonalite were intact. Test results were as follows:

Hole No.	Specimen No.	Specific Gravity	Schmidt No.	Ultimate Compressive Strength	Compres-sional Wave Velocity
				psi	fps
DV-CR-17	1	2.662	48.4	17,520	15,260
	2	2.636	50.7	18,580	15,930
	4	2.658	49.8	14,180	15,500
	6	2.642	48.8	10,500	15,390
	11	2.715	47.6	19,970	16,110
	17	2.664	48.2	11,820	13,730
	18	2.647	49.7	14,780	15,590
Average		2.660	49.0	15,340	15,360

Physical test results seemed to indicate that, while all of this core was relatively competent to very competent material, the

medium-grained rock was generally stronger than the coarse-grained rock. Thorough petrographic examination revealed that this variation in strength was not due entirely to variation in grain size, but rather to a significant difference in degree of recrystallization following shearing of this material (Section 4.3). All of the tonalite had been subjected to this in situ shearing action, but the medium-grained material had been completely recrystallized, voiding the zones of weakness brought about by shearing.

The effect of fractures, bands, and/or contacts on the medium-grained, recrystallized tonalite appeared to be quite varied. The presence of contacts or bands seemed to have the largest effect, apparently reducing strength by 30 to 60 percent (Hole DV-CR-39, Specimens 11, 15, 18, and 20). Fracturing appeared to reduce strength somewhat less drastically, particularly if the fractures were vertical or inclined at high angles (80 to 90 degrees) with respect to the horizontal.

Compressional wave velocities were found to be rather variable, but appeared to be substantially higher in those specimens containing quartz bands or contacts with dark gray amphibolite.

With the exception of Specimen 11 from Hole DV-CR-39, which contained a contact with dark gray amphibolite, elastic constants exhibited by the tonalite were generally rather high, particularly the static moduli. As indicated in the following tabulation, static

Hole No.	Specimen No.	Modulus						Poisson's Ratio	
		Young's		Bulk		Shear		Static	Dynamic
		Static	Dynamic	Static	Dynamic	Static	Dynamic		
		10^6 psi	10^6 psi	10^6 psi	10^6 psi	10^6 psi	10^6 psi		
DV-CR-17	1	11.0	8.6	9.2	2.5	4.2	4.6	0.30	--
	11	11.0	6.9	--	1.8	--	4.0	--	--
DV-CR-19	8	10.0	8.0	7.2	6.4	3.9	3.1	0.27	0.29
	11	9.6	7.5	5.6	5.2	4.0	3.0	0.22	0.26
	18	10.2	7.5	5.5	5.3	4.3	3.0	0.19	0.26
DV-CR-39	2	10.1	9.4	6.1	7.9	4.1	3.6	0.23	0.30
	11	6.7	9.1	3.6	8.2	2.8	3.4	0.19	0.32
Average		9.8	8.1	6.2	5.3	3.9	3.5	0.23	0.29

moduli, computed at 50 percent of ultimate strength, were usually 10 to 30 percent higher than their corresponding dynamic values.

The stress-strain curves from which static constants were derived exhibited very little hysteresis and, upon cycling, no appreciable residual strain. Most of the curves exhibited some upward curvature over the initial portions, possibly due to closure of the very fine horizontal cracks detected in the petrographic examination. Most of the tonalite specimens were quite brittle, generally exhibiting very little plastic deformation prior to catastrophic failure.

3.3 GABBRO

The rock core received from Holes DV-CR-24 and -40 was petrographically identified as dark gray gabbro. The material from Hole DV-CR-24 was coarse grained, while that from Hole DV-CR-40 was medium grained. The specimens from both holes had been sheared to various degrees.

As indicated by the following tabulation and by the detailed results given in Appendixes D and F, test results exhibited by the gabbro from the Vermillion study area were quite varied.

Hole No.	Specimen No.	Specific Gravity	Schmidt No.	Ultimate Uniaxial Compressive Strength	Compressional Wave Velocity
				psi	fps
Intact:					
DV-CR-40	2	2.807	55.5	47,730	22,790
	3	2.818	51.1	48,480	23,505
	5	2.801	--	50,580	23,180
	14	2.810	53.7	57,880	23,390
Average		2.809	53.4	51,170	23,220
Fractured:					
DV-CR-24	1	2.852	--	29,640	18,540
	2	2.875	57.3	24,000	21,575
	5	2.811	--	24,150	20,300
	9	2.878	56.4	24,590	18,655
	11	3.019	59.3	27,000	21,575
	14	2.836	--	14,700	21,060
	18	2.848	55.3	8,640	20,345
	22	2.856	57.6	23,090	19,770
DV-CR-40	4	2.799	51.6	17,420	23,235
	8	2.812	56.2	17,580	23,320
	12	2.778	--	33,940	22,735
	13	2.803	52.9	34,850	23,350
	20	2.815	54.9	16,060	23,030
	21	2.800	--	32,270	23,290
Average		2.842	55.7	23,420	21,480

Ultimate uniaxial compressive strength appeared to depend largely on nature and degree of fracturing present in the core, with fractured specimens exhibiting average ultimate strengths approximately 50 percent as great as those exhibited by the intact (macroscopically free of fractures, joints, etc.) core. The range in strength yielded by the fractured specimens was, however, quite large, and, while no definite boundaries and groupings were discernible, it appeared that the stronger of the fractured specimens contained approximately vertical and/or horizontal fractures while the weaker ones contained fractures inclined with respect to the horizontal.

Another possible cause of this wide range of strength is the variation in degree to which the gabbro specimens were recrystallized following the in situ shearing process previously mentioned. Petrographic examination revealed that while the stronger, medium-grained gabbro had been somewhat more sheared than the coarser material, it had also been recrystallized to a substantially greater degree. Therefore, what at first appears to be a variation due to nature and degree of fracturing might actually be the result of variation in degree of recrystallization, and is more probably a combination of the two.

Compressional wave velocities determined for the Vermillion area gabbro were generally quite high, particularly those exhibited by the medium-grained material (23,000 fps). These values were, however, similar in magnitude to those reported in Reference 3. There was no

apparent correlation between compressional wave velocity and ultimate uniaxial compressive strength. The fact that the fractured specimens also exhibited rather high velocities indicated that most of the fractures were tightly closed or well sealed.

Elastic constants exhibited by the coarse-grained gabbro, as indicated in the following tabulation, were relatively low, while those

Specimen No.	Modulus						Poisson's Ratio	
	Young's		Bulk		Shear		Static	Dynamic
	Static	Dynamic	Static	Dynamic	Static	Dynamic		
	10^6 psi	10^6 psi	10^6 psi	10^6 psi	10^6 psi	10^6 psi		
Hole DV-CR-40, Medium Grained:								
5	14.1	12.1	10.7	14.3	5.5	4.5	0.28	0.36
12	13.9	11.2	10.7	13.8	5.4	4.1	0.28	0.36
21	14.7	11.8	9.8	14.7	5.9	4.4	0.25	0.36
Average	14.2	11.7	10.4	14.3	5.6	4.3	0.27	0.36
Hole DV-CR-24, Coarse Grained:								
2	5.6	11.5	3.3	12.2	2.8	4.3	0.22	0.34
9	6.8	9.0	4.7	9.0	2.7	3.4	0.26	0.33
Average	6.2	10.2	4.0	10.6	2.8	3.8	0.24	0.34

exhibited by the medium-grained gabbro were very high. Also, the gabbro from Hole DV-CR-40 was quite brittle and exhibited no appreciable hysteresis; the coarser grained material from Hole DV-CR-24 exhibited some hysteresis. While the first inclination might be to attribute these differences primarily to variation in grain size and degree of recrystallization after shearing, it is also possible that the lower

elastic constants and larger hysteresis loops characteristic of the gabbro from Hole DV-CR-24 were the result of the many horizontal incipient fractures petrographically detected in the DV-CR-24 core. These horizontal discontinuities, while probably causing no appreciable reduction in ultimate uniaxial compressive strength (inclined fractures generally have most significant effect on uniaxial strength), could have contributed greatly to the larger axial deformations and somewhat lower wave velocities, and thus resulted in the lower moduli.

3.4 AMPHIBOLITE

Several specimens received from Hole DV-CR-39 were petrographically identified as amphibolite. All contained fractures, some of which were oriented at critical angles (inclined with respect to the plane of applied stress at an angle such that shear stresses of failure magnitudes are developed along these fractures at relatively low applied normal stresses). Detailed test results are given in Appendix E. A summary of the results is given below:

Hole No.	Specimen No.	Specific Gravity	Schmidt No.	Ultimate Uniaxial Compressive Strength	Compressional Wave Velocity	Hole No.	Specimen No.	Specific Gravity	Schmidt No.	Ultimate Uniaxial Compressive Strength	Compressional Wave Velocity
				psi	fps					psi	fps
Containing Nearly Vertical Fractures:						Containing Critically Oriented Fractures:					
DV-CR-39	8	2.883	51.2	21,520	21,090	DV-CR-39	4	2.870	52.1	16,240	21,120
	13	2.829	51.5	22,970	21,800		7	2.878	47.6	5,920	19,820
	19	2.822	54.1	23,790	21,000	Average		2.874	49.8	11,080	20,470
Average		2.845	52.3	22,760	21,300						

Although the data are rather limited in quantity, the results available appear to indicate two distinct groups of amphibolite: specimens containing nearly vertical (high angle) fractures and specimens containing critically oriented fractures. Expectedly, the core containing the nearly vertical fractures was somewhat stronger, exhibiting ultimate uniaxial compressive strengths averaging approximately twice as large as those exhibited by the specimens containing critically oriented fractures. Compressional wave velocities were relatively uniform throughout both groups.

Elastic constants were determined for one specimen and were comparable to the values given for the tonalite in Appendixes B, C, and E. Stress-strain curves revealed the specimen tested to be quite brittle. Upon cycling, no hysteresis or residual strain was evident.

3.5 GNEISS

The majority of the core received from Hole DV-CR-9 was petrographically identified as gneiss and exhibited considerable variation in composition. Ten representative specimens were tested. Detailed results are presented in Appendix A. A summary is given on the following page.

The majority of the gneiss from this hole was well foliated and contained relatively large amounts of mica. This well developed

Hole No.	Specimen No.	Specific Gravity	Schmidt No.	Ultimate Uniaxial Compressive Strength	Compres-sional Wave Velocity
				psi	fps
Poorly Foliated Granitic Gneiss:					
DV-CR-9	1	2.671	52.8	33,180	18,230
	7	2.676	--	22,850	18,300
Average		2.674	52.8	28,020	18,270
Well Foliated Mica Gneiss:					
DV-CR-9	3	2.745	50.1	15,680	18,555
	4	2.774	--	13,850	18,820
	8	2.755	38.6	18,700	17,630
	9	2.752	41.1	21,480	16,610
	10	2.765	35.6	14,360	17,540
	12	2.774	50.8	14,060	17,820
	18	2.707	38.3	14,140	17,950
	21	2.790	43.6	13,090	17,080
Average		2.758	42.6	15,670	17,750

foliation, varying in orientation from vertical to horizontal, was probably responsible for the relatively low (as compared to those exhibited by the granite gneiss) and varying ultimate uniaxial compressive strengths yielded by the mica gneiss. The high mica content resulted in somewhat higher densities.

The granitic gneisses tested were poorly foliated, somewhat less dense than the mica gneisses, and exhibited ultimate uniaxial

compressive strengths approximately twice as large as those yielded by the mica gneisses. These higher strengths were probably due to the absence of foliation rather than the difference in mineral composition.

Compressional wave velocities were rather uniform in spite of the variation in physical structure and mineral composition.

Elastic constants determined for the gneiss from the Vermillion study area were moderate in magnitude, and, as indicated in the following tabulation, were relatively uniform. Stress-strain curves

Hole No.	Specimen No.	Modulus						Poisson's Ratio	
		Young's		Bulk		Shear		Static	Dynamic
		Static	Dynamic	Static	Dynamic	Static	Dynamic		
		10^6 psi	10^6 psi	10^6 psi	10^6 psi	10^6 psi	10^6 psi		
DV-CR-9	7	10.4	--	7.8	--	4.1	--	0.29	--
	9	8.6	8.3	4.9	5.9	3.6	3.3	0.20	0.26
	10	9.5	8.6	4.9	7.0	4.0	3.3	0.18	0.30
Average		9.5	8.4	5.9	6.4	3.9	3.3	0.22	0.28

determined during the uniaxial compression tests revealed this material to be rather brittle, as very little plastic deformation was recorded prior to catastrophic rock failure. Upon cycling, only slight hysteresis and residual strain were exhibited.

3.6 GRANITE

Three specimens received from Hole DV-CR-9 were petrographically identified as red granite. Of these three, two were tested, yielding

ultimate uniaxial compressive strengths which averaged approximately 30,000 psi. As indicated in Appendix A, the granite tested from Hole DV-CR-9 exhibited physical test results which were very similar to those exhibited by the granitic gneisses from this same hole.

CHAPTER 4

SPECIAL TESTS

4.1 ANISOTROPY TESTS

Six rock specimens from the Vermillion area were selected and prepared for determination of compressional (dilatational) and shear velocities according to the ASTM proposed "Standard Method of Test for Laboratory Determination of Ultrasonic Pulse Velocities and Elastic Constants of Rock." The NX-diameter specimens were cut to lengths of 2 inches and ground on the ends to a tolerance of 0.001 inch. Four 1/2-inch-wide strips were also ground down the sides of the cylindrical surface at 90-degree angles. Velocities, densities, and dimensions were measured as specified in the proposed test method. Results of the velocity determinations are given in Table 4.1.

Compressional and shear velocities exhibited by the gabbro and amphibolite were exceptionally high, particularly those exhibited by the medium-grained gabbro. It should be noted, however, that the medium-grained gabbro also yielded several ultimate uniaxial compressive strengths in the range of 50,000 psi, tending to substantiate the high degree of competence for the intact material indicated by the high wave velocities. Only one amphibolite was tested, since amphibolite represented less than 10 percent of the core received from the Vermillion study area.

The wave velocities exhibited by the one mica gneiss specimen, representing only approximately 10 percent of the core received, were somewhat scattered, considerably higher in the axial and one horizontal direction than the other horizontal direction. The low velocity could probably be attributed to the seam of quartz along the side of the specimen through which the compressional wave of the lowest velocity passed. These quartz seams and bands were typical of the mica gneiss from Hole DV-CR-9.

The tonalite from Holes DV-CR-17 and -19 exhibited moderate wave velocities, generally rather uniform.

Deviations from the average compressional wave velocity were relatively low for the gabbros, tonalites, and amphibolite--not exceeding 5 percent. The deviation exhibited by the mica gneiss was quite high (15.1 percent), however, probably due again to the seam of quartz passing along one side of the specimen.

A compilation of the elastic properties computed from the compressive and shear velocities and specific gravity is given in Table 4.2. However, discretion must be used in utilizing the moduli results as experimental errors are introduced when the differences in velocities are significant. The proposed ASTM test method states that the equations for computation of elastic moduli should not be used if "any of the three compressional wave velocities varies by more than 2 percent from their average value. The error in E and G

due to both anisotropy and experimental error then does not exceed 6 percent." Naturally, the effect of the error is compounded by greater differences in the three-directional velocity measurements.

The 2 percent allowable deviation proposed by ASTM appears to be unrealistic since laboratory-determined values of compressional and shear wave velocities are reproducible within a deviation from the average of only 2 to 3 percent. Thus, it would appear that the point of division between isotropy and anisotropy would more realistically be in the range of 5 to 8 percent deviation from the average. It should be kept in mind, however, that this greater deviation would also allow a larger error in the computed values of E (modulus of elasticity) and G (shear modulus).

4.2 COMPARATIVE TENSILE TESTS

Six NX-diameter rock specimens were selected to represent the variation of rock type present in the core received from the drill holes in the Vermillion area. The specimens were prepared and tested for tensile strength according to the ASTM proposed "Standard Method of Test for Direct Tensile Strength of Rock Core Specimens." For comparative purposes, tensile splitting tests were conducted on specimens cut adjacent to the direct tensile test specimens. The test results are given in Table 4.3.

Three specimens, DV-CR-9, Specimen 17, DV-CR-39, Specimen 6, and

DV-CR-40, Specimen 19, exhibited direct tensile strengths greater than the adhesive strengths of the several types of epoxies used. Therefore, ultimate direct tensile strengths of these specimens could not be determined. It should be noted, however, that the direct tensile strengths of the three specimens in all cases exceed 1,500 psi, as stresses of this magnitude did not result in rock failure.

The two tonalite specimens tested yielded similar results, with direct tensile strength generally being approximately 75 percent as large as the indirect strength. In homogeneous specimens, the indirect strength should be expected to be greater, since the specimen subjected to direct tension is more prone to failure at the point of minimum strength.

The gneiss specimen yielded an ultimate strength in direct tension somewhat higher than the strength determined by splitting. This rather unusual occurrence was probably due to high-angle foliation present in the gneiss which significantly weakened the core along longitudinal planes while having little, if any, detrimental effect on strength along horizontal planes.

The two gabbro specimens tested exhibited somewhat different test results, with the medium-grained rock appearing to be significantly stronger, both in direct and indirect tension, than the coarse-grained specimen. This variation could probably be attributed to the more extensive recrystallization process to which the

medium-grained gabbro had been subjected after in situ shearing had taken place. While the coarser grained material had been somewhat less sheared, it had been recrystallized only to a relatively minor degree.

The amphibolite was quite strong in tension, exhibiting an unusually high indirect strength of 3,020 psi and a direct strength greater than the 1,730-psi adhesive strength of the epoxy.

4.3 PETROGRAPHIC REPORT

4.3.1 Samples. Six boxes of NX core from Koochiching, Lake, and St. Louis Counties, Minnesota, were received in September 1969 for testing. Each box contained about 15 feet of core which represented depths to 200 feet.

The cores were inspected to select representative pieces from all significant rock types for petrographic examination. The cores are described as follows.

1. Hole DV-CR-9. The core was red, coarse-grained granite; light gray, coarse-grained gneiss; and black, medium-grained gneiss. The entire core appeared to be unweathered and massive.

Specimens 3, 7, and 8 contained sealed fractures. Specimens 6, 13, and 16 were red, coarse-grained granite. There were no apparent flow structures. Specimens 1, 7, 11, and 15 were light gray and pink, medium-grained granitic gneiss. These specimens were massive and

contained a poorly developed flow structure. Specimens 2 through 5, 8, 9, 10, 12, 14, and 17 through 21 were dark to medium gray, fine-grained, banded mica gneiss. The foliation ranged from vertical to nearly horizontal.

2. Hole DV-CR-17. The entire core was brownish-gray, medium- to coarse-grained tonalite. The specimens were massive and unweathered.

3. Hole DV-CR-19. The entire core was gray, medium-grained tonalite. This core was similar to DV-CR-17. The core was unweathered but did contain several sealed fractures.

4. Hole DV-CR-24. The entire core was dark gray, coarse-grained gabbro and contained fractures frequently masked by the coarse texture of the rock.

5. Hole DV-CR-39. The core was dark gray, medium-grained amphibolite; pink, medium-grained tonalite; and white and black, medium-grained tonalite. Most of the specimens contained fractures, but none of the specimens appeared weathered.

Specimens 3 through 10, 12, 13, 16, 17, and 19 were dark gray amphibolite. Most specimens contained a well developed low-angle foliation. All of the specimens contained high angle or vertical fractures, most of which were sealed.

Specimens 2 and 18 were white and black, medium-grained tonalite. Specimen 2 contained sealed vertical fractures, and

Specimen 18 contained a high angle quartz band and sealed fractures at the critical angle.

Specimens 11, 14, 15, and 20 were pink, medium-grained tonalite and also contained contacts with the dark gray amphibolite. Specimen 20 contained a high angle quartz band.

6. <u>Hole DV-CR-40</u>. The entire core was dark gray, medium-grained gabbro. Specimens 2, 3, 5, and 14 were massive and the remaining specimens were fractured. None of the specimens appeared weathered, and most of the fractures were sealed.

The specimens selected for petrographic examination were:

Hole No.	CD Serial No.	Specimen No.	Approximate Depth	Rock Description
			ft	
DV-CR-9	SAMSO-10, DC-1	6	51	Pink, coarse-grained granite
		11	100	Light gray, medium-grained gneiss
		14	130	Dark gray, fine-grained gneiss
DV-CR-17	SAMSO-10, DC-2	15	146	Gray-brown, coarse-grained tonalite
DV-CR-19	SAMSO-10, DC-3	20	185	Gray, medium-grained tonalite
DV-CR-24	SAMSO-10, DC-6	17	156	Dark gray, coarse-grained gabbro
DV-CR-39	SAMSO-10, DC-4	2	21	White and black, medium-grained tonalite

(Continued)

Hole No.	CD Serial No.	Specimen No.	Approximate Depth	Rock Description
			ft	
DV-CR-39	SAMSO-10, DC-4	14	134	Pink and black, medium-grained tonalite
		17	166	Black, medium-grained amphibolite
DV-CR-40	SAMSO-10, DC-5	20	181	Dark gray, medium-grained gabbro

4.3.2 Test Procedure. Each core specimen was sawed axially. One sawed surface of each specimen was polished and photographed. Composite samples were obtained from the whole length of the remaining half of each specimen. The composite samples were ground to pass a No. 325 sieve (44 μm). X-ray diffraction (XRD) patterns were made on each sample on a tightly packed powder representing the entire length of the specimen. All XRD patterns were made using an XRD-5 diffractometer with nickel-filtered copper radiation. The samples X-rayed are listed below:

Hole No.	Specimen No.
DV-CR-9	6
DV-CR-9	11
DV-CR-9	14
DV-CR-17	15
DV-CR-19	20
DV-CR-24	17

(Continued)

Hole No.	Specimen No.
DV-CR-39	2
DV-CR-39	14
DV-CR-39	17
DV-CR-40	20

Small portions of the powdered samples were tested with dilute hydrochloric acid and with a magnet to determine whether carbonate minerals or magnetite were present.

The polished surface of each section was examined with a stereomicroscope. Thin sections were prepared from each section of core and examined with a polarizing microscope. A point count modal analysis was made on each thin section, in which 500 points were counted.

4.3.3 Results. The cores examined from the Vermillion area can be divided into five groups: tonalites, gabbros, amphibolites, gneisses, and granites (References 4 and 5). The cores were taken from the late and middle Precambrian rocks in the southern extension of the Canadian Shield in north-central Minnesota.

The gabbros were part of the late Precambrian Duluth Complex and may represent the anorthosite gabbro member of the complex. The granites, gneisses, and most of the tonalites were part of the Vermillion Granite. The amphibolites and some of the tonalites were from the Giant's Range Granite. The Vermillion and Giant's Range Granites are Algoman intrusives in which many rock types are included,

and the Duluth Complex is a Keewenawan Complex of intrusives and flows (Reference 6). The modal compositions and the bulk compositions by XRD of each section are shown in Tables 4.4 through 4.8. The core sections examined are discussed below:

1. Tonalites. Most of the rocks from the Vermillion Granite area were gray-brown, coarse-grained tonalites (Table 4.4). A white-pink tonalite was present in minor amounts in Core DV-CR-39 where it intruded an amphibolite. The tonalites differed in composition and texture and probably represented separate intrusions associated with different igneous complexes.

Section 15 of Core DV-CR-17 was taken from the Vermillion Granite area and represents an important phase of that rock. The section was brownish-gray, coarse-grained tonalite (Figure 4.1). The sericitic alteration of the plagioclase obscured the twinning; a few grains showed compositional zoning. The quartz ranged from slightly to highly strained, and biotite was broken and altered to chlorite. The microcline was not altered or broken. There were a few microfractures present, but these were minor features.

Section 20 of Core DV-CR-19 had a composition similar to Section 15 of DV-CR-17 (Table 4.4) but had been severely sheared (Figure 4.1). Most of the grains were anhedral and fractured. The plagioclase was almost completely altered to sericite and the quartz was severely strained. The microcline appeared to be unaffected and may

have been introduced after deformation and alteration. The shear planes were not evident and may have been destroyed during later metamorphism.

Section 2 of Core DV-CR-39 was taken from the Giant's Range area. It contained about 60 percent plagioclase, 30 percent quartz, and less than 5 percent dark minerals (Figure 4.2). The section was medium-grained with cataclastic texture. Plagioclase, with an anorthite content of 30 percent, formed subhedral grains with granulated borders severely altered to sericite. Several of the grains were zoned. The quartz was sheared and strained, and most of the biotite had altered to chlorite. The microcline was very fresh and did not appear to be sheared or altered. Muscovite and epidote had formed in the plagioclase and carbonate had been introduced along fractures.

2. Gabbros. The rocks from Cores DV-CR-24 and -40 were equigranular and primarily composed of plagioclase and pyroxene (Table 4.5). Primary flow structures were not detected in any of the sections (Figure 4.3). Plagioclase and pyroxene were slightly altered in DV-CR-24, but DV-CR-40 had been highly sheared and altered.

Section 17 of Core DV-CR-24 was dark gray, coarse-grained soda gabbro (Figure 4.3). Plagioclase, containing 48 percent anorthite, formed large well developed lath-shaped crystals that exhibited albite and pericline; or albite and Carlsbad; or albite, pericline, and Carlsbad twinning. The pyroxenes in the section were diopside and

hypersthene. The diopside was more altered than hypersthene, perhaps to amphibole in part, and generally subhedral to anhedral. Small amounts of biotite were usually associated with the diopside and were severely altered to chlorite. Large grains of magnetite and ilmenite were common throughout the section.

Section 20 of Core DV-CR-40 had been fractured and moderately altered (Figure 4.3), but the composition was similar to that of Section 17 of DV-CR-24 (Table 4.5). The plagioclase was partially altered to sericite and fractured. Microscopic and macroscopic fractures were common. Pyroxene had been altered to chlorite and magnetite and reduced to anhedral masses.

3. Amphibolites. Part of Core DV-CR-39 was taken from an area mapped as the Giant's Range Granite and may represent an older rock intruded and metamorphosed by the granites, as amphibolites in this granite are usually relics of the intruded country rock. The amphibolites consisted predominantly of hornblende and plagioclase with minor amounts of biotite (Table 4.6). These rocks were dark gray and medium-grained except along contacts with the Giant's Range rocks. Along these contacts, composite rocks made up of intermixed amphibolite and igneous rock (migmatites) were commonly formed. These migmatites had compositions similar to feldspathic amphibolites (Table 4.6).

Section 14 of Core DV-CR-39 was from a contact zone (Figure 4.4)

where feldspathic amphibolite was formed by injection of a tonalite into the amphibolite. The tonalite partially assimilated the amphibolite during intrusion, producing a gradational rather than a sharp contact between the two rock types. The plagioclase had been severely fractured and completely altered to sericite. The quartz had been fractured and strained, and the hornblende had been fractured and altered. Chlorite was common as an alteration product of biotite and hornblende. The texture of this section was cataclastic.

Section 17 of Core DV-CR-39 was typical of the amphibolites away from the contact areas. It was dark gray, medium-grained amphibolite containing a small amount of biotite (Figure 4.4). Amphibole was anhedral to subhedral hornblende, slightly altered to chlorite along healed microfractures. Plagioclase was completely altered to anhedral masses of sericite. Biotite was usually bent and altered to chlorite.

4. Gneisses. Parts of Core DV-CR-9 were typical of the gneisses in the Vermillion batholith, and ranged in composition from granitic to tonalitic (Table 4.7). They were typically coarse-grained and ranged from very dark to light gray in color (Figure 4.5).

Section 11 of Core DV-CR-9 was a gray and pink, coarse-grained gneiss (Figure 4.5) with a granitic composition, consisting of quartz, plagioclase, and microcline. The plagioclase, containing 20 percent anorthite, was in part altered to sericite and the biotite was

altered to chlorite. Microcline was not altered or fractured. Quartz was not severely strained. Myrmekitic intergrowths were common along contacts between feldspar and quartz.

Section 14 of Core DV-CR-9 was a black, medium-grained mica gneiss composed of quartz, plagioclase, and biotite (Figure 4.5). There was a well developed microscopic foliation masked by the dark color of the rock. The rock apparently had been recrystallized, resulting in a uniform grain size and grain shape. Most of the plagioclase, containing 32 percent anorthite, was twinned and altered.

5. Granites. Section 6 of Core DV-CR-9 was typical of the granites (Table 4.8). It was a red, coarse-grained potash granite containing a few healed fractures (Figure 4.2). The microcline was subhedral and unaltered, and the quartz was slightly strained. Plagioclase, with an anorthite content of 20 percent, was altered to sericite, and biotite was almost completely altered to chlorite. No flow structure or foliation was detected.

4.3.4 Summary. Petrographic examination of ten sections of core from six holes in the southern Canadian Shield of north-central Minnesota indicated that five rock types were represented: tonalites, gabbros, amphibolites, gneisses, and granites. The tonalites and the gabbros were the most abundant rock types in the cores. Differences in the compressive strength and elastic properties among the rocks of each type seem to be associated with the number and inclination of

fractures, whether the fractures were sealed or open, and the amount of recrystallization during metamorphism. The mineral compositions are summarized in Tables 4.4 through 4.8, and the sections examined are illustrated in Figures 4.1 through 4.5.

TABLE 4.1 VELOCITY DETERMINATIONS

		Velocity[a]		
		Compressional		Shear
		fps		fps
Hole DV-CR-9, Specimen 17:				
Mica gneiss		23,030		11,930
Depth: 160 feet		17,730		10,580
Specific gravity: 2.802		21,885		10,720
Compressional deviation:[b] 15.1 pct				
	Average	20,880	Average	11,080
Hole DV-CR-17, Specimen 5:				
Medium- to coarse-grained tonalite		17,540		10,060
Depth: 46 feet		19,180		11,630
Specific gravity: 2.681		18,550		10,940
Compressional deviation: 4.8 pct				
	Average	18,420	Average	10,880
Hole DV-CR-19, Specimen 13:				
Medium-grained tonalite		17,050		9,900
Depth: 119 feet		17,910		10,640
Specific gravity: 2.668		17,910		10,290
Compressional deviation: 3.2 pct				
	Average	17,620	Average	10,280
Hole DV-CR-24, Specimen 10:				
Coarse-grained gabbro		21,040		10,650
Depth: 88 feet		20,210		11,750
Specific gravity: 2.857		20,740		10,790
Compressional deviation: 2.2 pct				
	Average	20,660	Average	11,060
Hole DV-CR-39, Specimen 6:				
Amphibolite		22,150		11,380
Depth: 60 feet		21,840		11,900
Specific gravity: 2.953		21,870		12,180
Compressional deviation: 0.9 pct				
	Average	21,950	Average	11,820
Hole DV-CR-40, Specimen 19:				
Medium-grained gabbro		23,400		11,700
Depth: 172 feet		22,760		12,240
Specific gravity: 2.842		22,790		12,340
Compressional deviation: 1.8 pct				
	Average	22,980	Average	12,090

[a] First velocity listed is in axial (longitudinal) direction; other two are on mutually perpendicular, diametral (lateral) axes.

[b] Maximum percent deviation from the average of the compressional wave velocity.

TABLE 4.2 DYNAMIC ELASTIC PROPERTIES

Hole No.	Specimen No.	Moduli Young's	Moduli Shear	Moduli Bulk	Poisson's Ratio
		10^6 psi	10^6 psi	10^6 psi	
DV-CR-9	17	14.1	5.4	12.9	0.32
		10.3	4.2	6.2	0.22
		11.6	4.3	12.3	0.34
Average		12.0	4.6	10.5	0.29
DV-CR-17	5	9.2	3.7	6.2	0.25
		11.8	4.9	6.8	0.21
		10.4	4.2	6.5	0.23
Average		10.5	4.3	6.5	0.23
DV-CR-19	13	8.8	3.5	5.8	0.25
		10.0	4.1	6.1	0.23
		9.6	3.8	6.4	0.25
Average		9.5	3.8	6.1	0.24
DV-CR-24	10	11.6	4.4	11.2	0.33
		13.2	5.3	8.6	0.24
		11.7	4.5	10.5	0.31
Average		12.2	4.7	10.1	0.29
DV-CR-39	6	13.6	5.2	12.7	0.32
		14.5	5.6	11.4	0.29
		15.0	5.9	11.1	0.28
Average		14.4	5.6	11.7	0.30
DV-CR-40	19	14.0	5.2	14.0	0.33
		14.9	5.7	12.1	0.30
		15.1	5.8	12.1	0.29
Average		14.7	5.6	12.7	0.31

TABLE 4.3 TENSILE STRENGTH DETERMINATIONS

Hole No.	Specimen No.	Depth	Tensile Strength		Direct/ Splitting Strength	Core Description
			Splitting	Direct		
		feet	psi	psi	pct	
DV-CR-9	17	160	1,340	(1,700)[a]	(127)[a]	Gneiss (high angle foliation)
DV-CR-17	5	46	1,180	830	70	Tonalite
DV-CR-19	13	119	1,220	950	78	Tonalite
DV-CR-24	10	88	1,010	380	38	Gabbro (coarse-grained)
DV-CR-39	6	60	3,020	(1,730)[a]	(57)[a]	Amphibolite
DV-CR-40	19	172	1,860	(1,570)[a]	(84)[a]	Gabbro (medium-grained)

[a] Specimen strength in direct tension was greater than those of available epoxies. Strengths reported are greatest adhesive strengths observed; little actual rock failure occurred.

TABLE 4.4 COMPOSITION OF TONALITES

Constituent	Modal Composition[a]			Bulk Composition[b]		
	DV-CR-17 Section 15	DV-CR-19 Section 20	DV-CR-39 Section 2	DV-CR-17 Section 15	DV-CR-19 Section 20	DV-CR-39 Section 2
Quartz	29	30	33	Abundant	Same	Same
Plagioclase	48	45	58	Abundant	Same	Slightly more
Microcline	18	20	5	Abundant	Same	Much less
Biotite	2	1	1	Present	Same	Same
Chlorite	--	3	1	--	Present	Present
Magnetite	Trace	Trace	Trace	Trace	Same	Same
Apatite	Trace	Trace	Trace	--	--	--
Sphene	Trace	--	--	--	--	--
Zircon	Trace	Trace	Trace	--	--	--
Calcite	Trace	Trace	Trace	--	--	--
Epidote	--	--	Trace	--	--	--
Muscovite	--	--	Trace	--	--	--

[a] Modal composition based on count of 500 points in each thin section.
[b] Bulk composition by X-ray diffraction of powder sample. Compositions of DV-CR-19, Section 20, and DV-CR-39, Section 2, are compared with that of DV-CR-17, Section 15.

TABLE 4.5 COMPOSITION OF GABBROS

Constituent	Modal Composition[a]		Bulk Composition[b]	
	DV-CR-40 Section 20	DV-CR-24 Section 17	DV-CR-40 Section 20	DV-CR-24 Section 17
Plagioclase	88	85	Abundant	Same
Pyroxene	8	10	Minor	Slightly more
Magnetite	3	2	Present	Same
Ilmenite	--	2	--	Present
Biotite	Trace	Trace	--	--
Chlorite	Trace	Trace	--	--

[a] Modal composition based on count of 500 points in each thin section.

[b] Bulk composition by X-ray diffraction of powder sample. Composition of DV-CR-24, Section 17, is compared with that of DV-CR-40, Section 20.

TABLE 4.6 COMPOSITION OF AMPHIBOLITES

Constituent	Modal Composition[a] DV-CR-39		Bulk Composition[b] DV-CR-39	
	Section 17	Section 14	Section 17	Section 14
Quartz	--	20	--	Abundant
Plagioclase	39	41	Abundant	Same
Biotite	1	4	Trace	Minor
Chlorite	8	6	Minor	Minor
Hornblende	52	28	Abundant	Slightly less
Magnetite	--	Trace	--	--
Zircon	--	Trace	--	--

[a] Modal composition based on count of 500 points in each thin section.

[b] Bulk composition by X-ray diffraction of powder sample. Composition of Section 14 is compared with that of Section 17.

TABLE 4.7 COMPOSITION OF GNEISSES

Constituent	Modal Composition[a] DV-CR-9		Bulk Composition[b] DV-CR-9	
	Section 11	Section 14	Section 11	Section 14
Quartz	29	30	Abundant	Same
Plagioclase	25	34	Abundant	Slightly more
Microcline	32	--	Abundant	--
Biotite	8	33	Minor	Much more
Chlorite	5	--	Minor	Trace
Magnetite	Trace	2	--	Trace
Apatite	Trace	--	--	--
Sphene	Trace	--	--	--
Zircon	Trace	--	--	--

[a] Modal composition based on count of 500 points in each thin section.

[b] Bulk composition by X-ray diffraction of powder sample. Composition of Section 14 is compared with that of Section 11.

TABLE 4.8 COMPOSITION OF A GRANITE, CORE DV-CR-9, SPECIMEN 6

Constituent	Modal Composition[a]	Bulk Composition[b]
Quartz	30	Abundant
Microcline	41	Abundant
Plagioclase	19	Common--much less than microcline
Biotite	Trace	Present
Chlorite	5	Minor
Magnetite	2	Present
Calcite	2	Present
Zircon	Trace	--
Apatite	Trace	--

[a] Modal composition based on count of 500 points in each thin section.

[b] Bulk composition by X-ray diffraction of powder sample.

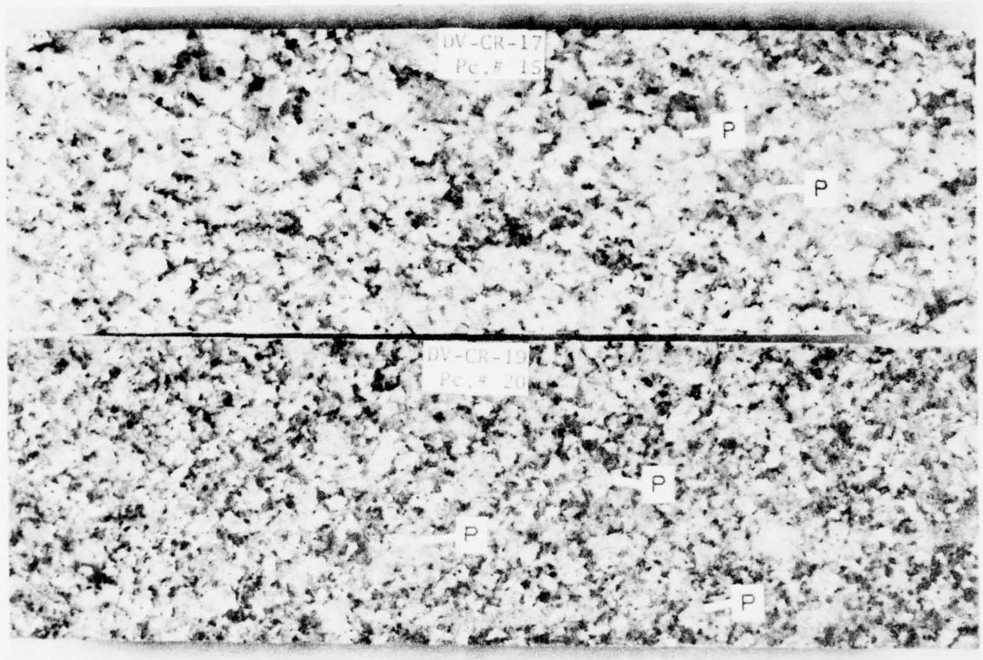


Figure 4.1 Tonalite Specimens DV-CR-17, Section 15, and DV-CR-19, Section 20. DV-CR-17, Section 15, shows typical coarse-grained tonalite. Several plagioclase grains show zoning (P). The dark band running the length of the core is a healed fracture. DV-CR-19, Section 20, shows a finer grain size than the preceding tonalite. Reduction in grain size was apparently the result of shearing. The plagioclase is zoned.

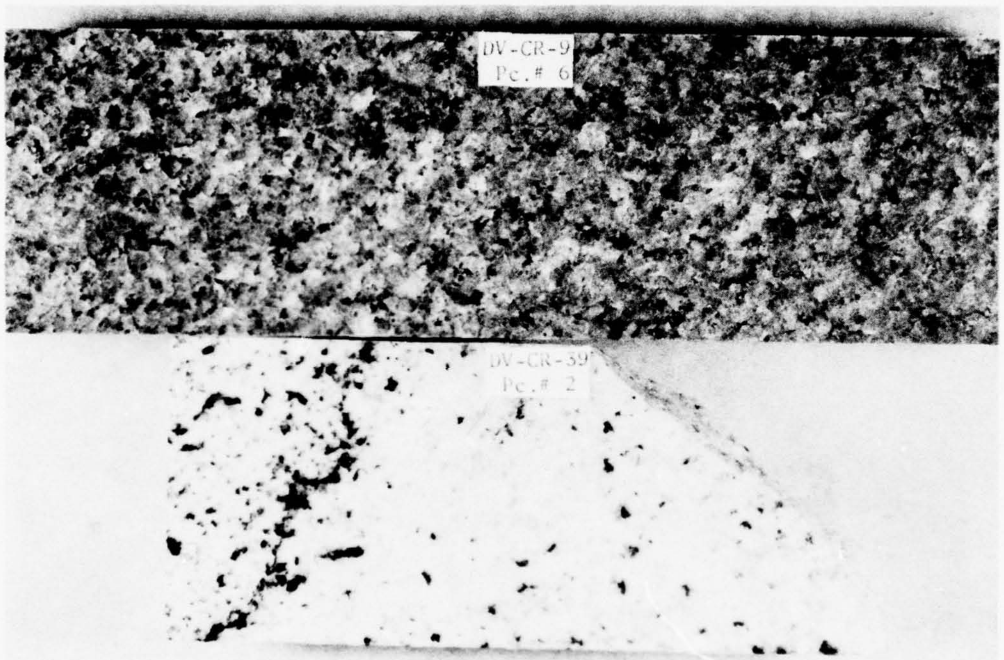


Figure 4.2 Granite Specimen DV-CR-9, Section 6, and tonalite Specimen DV-CR-39, Section 2. DV-CR-9, Section 6, shows typical coarse-grained, intact granite. Section shows no flow structures. DV-CR-39, Section 2, shows typical light colored tonalite. Left side is severely sheared and has undergone considerable reduction in grain size.

Figure 4.3 Gabbro Specimens DV-CR-24, Section 17, and DV-CR-40, Section 20. DV-CR-24, Section 17, shows coarse-grained, equigranular texture of the gabbro. Medium gray areas without crystal shape are ilmenite and magnetite. DV-CR-40, Section 20, is typical of the sheared gabbro. Narrow white lines are sealed shear fractures. Small white specks are magnetite. Section shows finer grain size than DV-CR-24, Section 17.

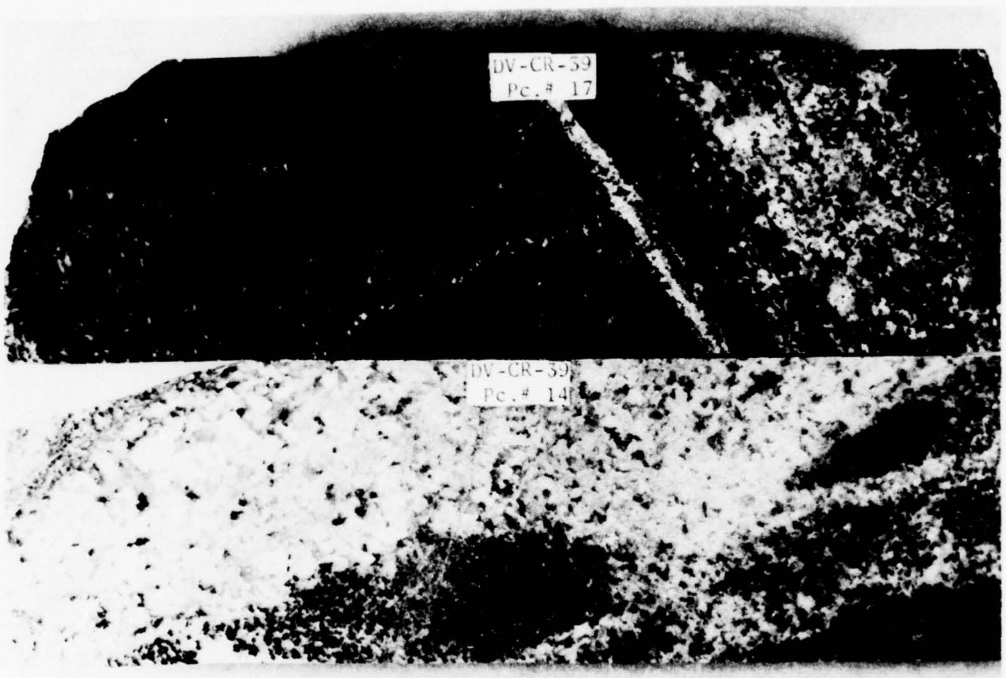


Figure 4.4 Amphibolite Specimen DV-CR-39, Sections 14 and 17. Section 17 shows low angle foliation and granitic inclusion. Perpendicular to the foliation are several healed shear fractures. Section 14 shows a typical contact between the amphibolite (right) and the tonalite (left). The tonalite has partially assimilated the amphibolite. The center of the core is cut by three chloritized fractures.

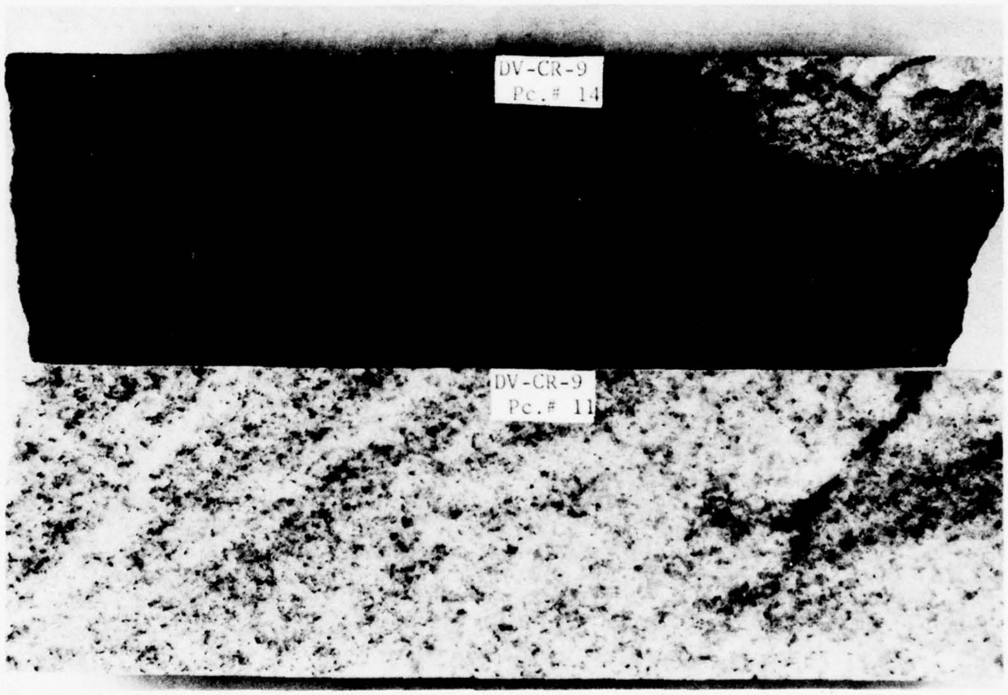


Figure 4.5 Gneiss Specimen DV-CR-9, Sections 11 and 14. DV-CR-9, Section 14, shows dark fine-grained gneiss. Foliation is difficult to detect but is nearly vertical. Note the inclusion of granite gneiss similar to DV-CR-9, Section 11. DV-CR-9, Section 11, shows high angle foliation and variation in grain size from medium to coarse.

CHAPTER 5

DISCUSSION AND CONCLUSIONS

5.1 DISCUSSION

The nature of the objective of these rock quality tests dictates overall evaluation of the core on a hole-to-hole basis. In the instances where individual holes yielded core of only one rock type (DV-CR-17, -19, -24, and -40), the evaluation of the hole will, of course, be dictated by characteristics of the particular rock type. In those instances, however, where several rock types are represented in a single hole, the evaluation of the hole will necessarily reflect the quality of the least competent rock type tested. It should be noted here, however, that differences in rock type are not commensurate with nonuniformity as described herein; rather uniformity is used to describe the physical characteristics of the material.

To facilitate evaluation of the Vermillion study area in this manner, a rock quality chart (Figure 5.1) was prepared. Ultimate uniaxial compressive strengths depicted on this chart were expressed in one of three categories: poor (less than 8,000 psi), marginal (8,000 to 12,000 psi), and good (above 12,000 psi). Locations of the individual drill holes are shown in Figure 5.2.

5.2 CONCLUSIONS

On the basis of test results exhibited by the specimens of rock

core received from the Vermillion study area, the following conclusions appear to be justified:

1. The rock core received from the Duluth-Vermillion area was petrographically identified as predominantly tonalite and gabbro, with relatively minor amounts of amphibolite, granite, and gneiss.

2. Many specimens contained fractures which ranged in orientation from vertical to horizontal. Several specimens contained bands and/or contacts with other types of rock.

3. The tonalite from this area was found to be relatively competent to very competent rock, depending on nature and degree of fracturing, and on the extent to which the rock had been recrystallized after shearing. The intact medium-grained tonalite, which had been subjected to extensive recrystallization, was very competent. The fractured and/or banded medium-grained tonalite was significantly weaker, but was still relatively competent material. The coarser grained tonalite (slightly recrystallized) was also relatively competent, but slightly weaker than the fractured and/or banded, medium-grained material, apparently indicating the lack of recrystallization of sheared material to be a more significant factor in the determination of rock quality than fracturing and/or banding.

4. The gabbro from this area was rather variable, ranging from relatively competent to very competent material. The intact rock was quite uniform and very competent, exhibiting an average ultimate

uniaxial compressive strength of 51,170 psi. The fractured gabbro was generally 30 to 70 percent weaker than the intact core, but in only one case did the ultimate strength fall below 14,000 psi (8,640 psi).

5. The gneiss from this area, all removed from Hole DV-CR-9, varied from well foliated, mica gneiss to poorly foliated granitic gneiss. The well foliated mica gneiss exhibited rather uniform physical properties and was relatively competent material. The poorly foliated granitic gneiss (two specimens) was somewhat stronger, probably due to the absence of planes of foliation.

6. Amphibolite was present in rather small quantities in Hole DV-CR-39, and exhibited the only ultimate uniaxial compressive strength from the entire area lower than 8,000 psi. All of the specimens were fractured, a factor which probably contributed significantly to the varied and sometimes low strengths. Approximately 11 percent of the core from the Duluth-Vermillion study area was amphibolite.

7. Three specimens received from this area were granite, and generally exhibited physical properties very similar to those exhibited by the granitic gneiss from the same hole (DV-CR-9).

8. Elastic constants determined for the rock core from this area were generally moderate to high, with the medium-grained gabbro yielding several very high values (average static Young's modulus of

14.2×10^6 psi). Interestingly, the lowest static moduli observed were determined on the coarse-grained gabbro, which had been only slightly, if at all, recrystallized after being subjected to in situ shearing. Generally, static moduli were slightly higher than their corresponding dynamic values, while static values of Poisson's ratio were usually lower than the dynamic values.

9. All of the material tested from this area was quite brittle, exhibiting little or no plastic deformation prior to failure.

10. With the exception of curves determined for the coarse-grained gabbro (had been sheared but not significantly recrystallized), stress-strain curves determined for the rock types from this area showed little or no upward concavity over the initial portions of curves, a phenomenon which, if present, is generally accredited to crack closure during the initial stages of loading. Except for the curves exhibited by the coarse-grained gabbro, little or no hysteresis or residual strain was detected.

11. Compressional wave velocities exhibited by the material from the Vermillion area were generally moderate in magnitude, except for the very high velocities determined on the recrystallized, medium-grained gabbro.

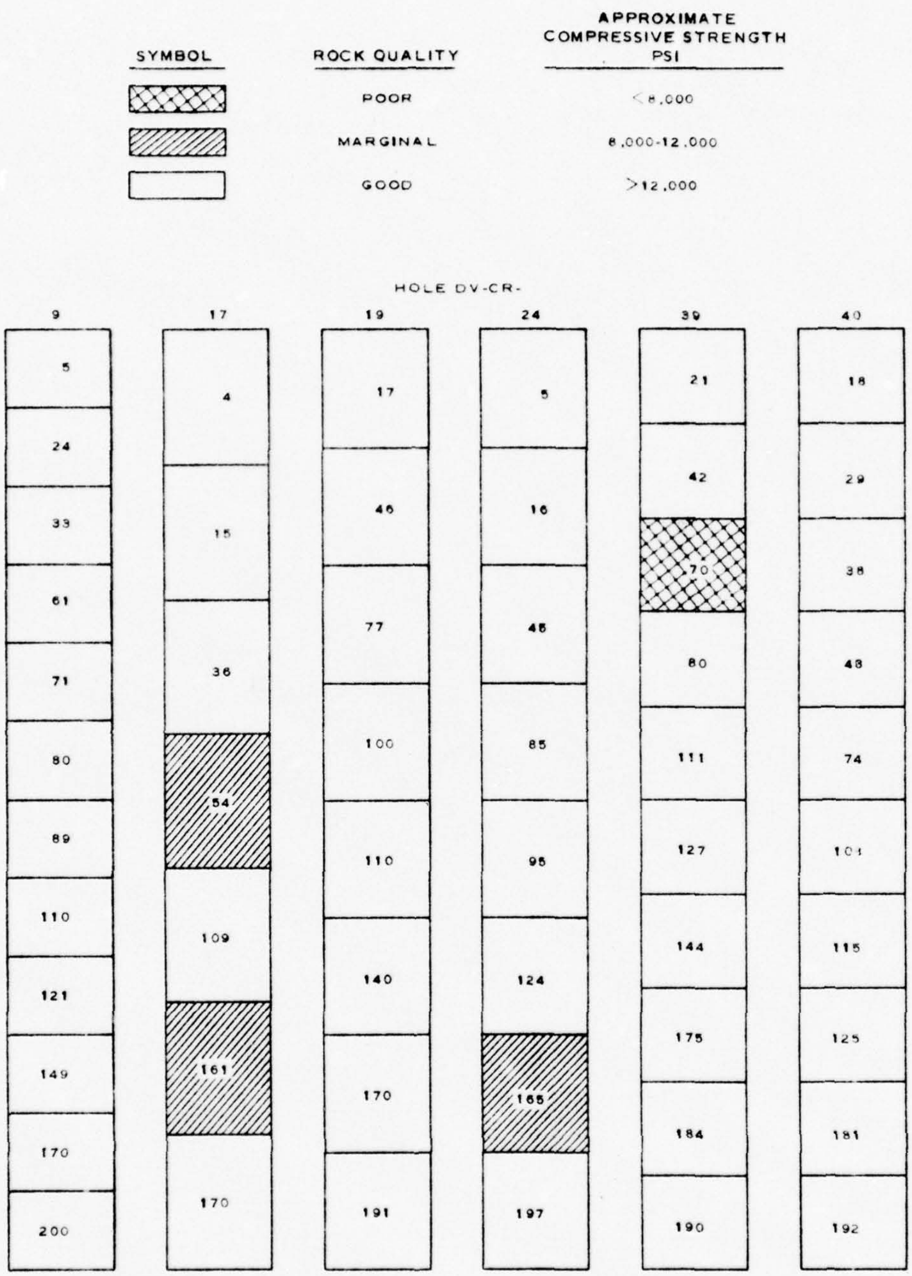
12. Generally, the material from this area was relatively isotropic, excepting the mica gneiss, which appeared very anisotropic. This anisotropy was probably more a reflection on the fractured

quartz seam along one side of the specimen than an indication of general anisotropy in the mica gneiss itself.

13. Tensile strengths exhibited by the gneiss, amphibolite, and medium-grained gabbro were unusually high; those exhibited by the tonalite and coarser grained gabbro were somewhat lower but still rather high.

14. Evaluation on a hole-to-hole basis indicates the tonalite represented by specimens from Hole DV-CR-19 to be quite uniform and very competent. This material should offer very good possibilities as a competent hard rock medium. The tonalite, medium-grained gabbro, and granite and granitic gneiss representing Holes DV-CR-17, -40, and -9, respectively, exhibited physical properties typical of relatively competent to very competent material, and all should offer reasonably good possibilities as competent media. The coarse-grained gabbro from Hole DV-CR-24 and the amphibolite and tonalite from Hole DV-CR-39 were generally marginal to relatively competent in quality, with only one specimen (DV-CR-39, Specimen 7, an amphibolite) yielding an ultimate uniaxial compressive strength characteristic of incompetent rock.

Evaluations have been based on rather limited data, and therefore, more extensive investigation will be required in order to accurately assess the areas under consideration.



NOTE: INDIVIDUAL NUMBERS WITHIN BLOCKS INDICATE DEPTHS OF TEST SPECIMENS.

Figure 5.1 Depth versus quality for individual holes.

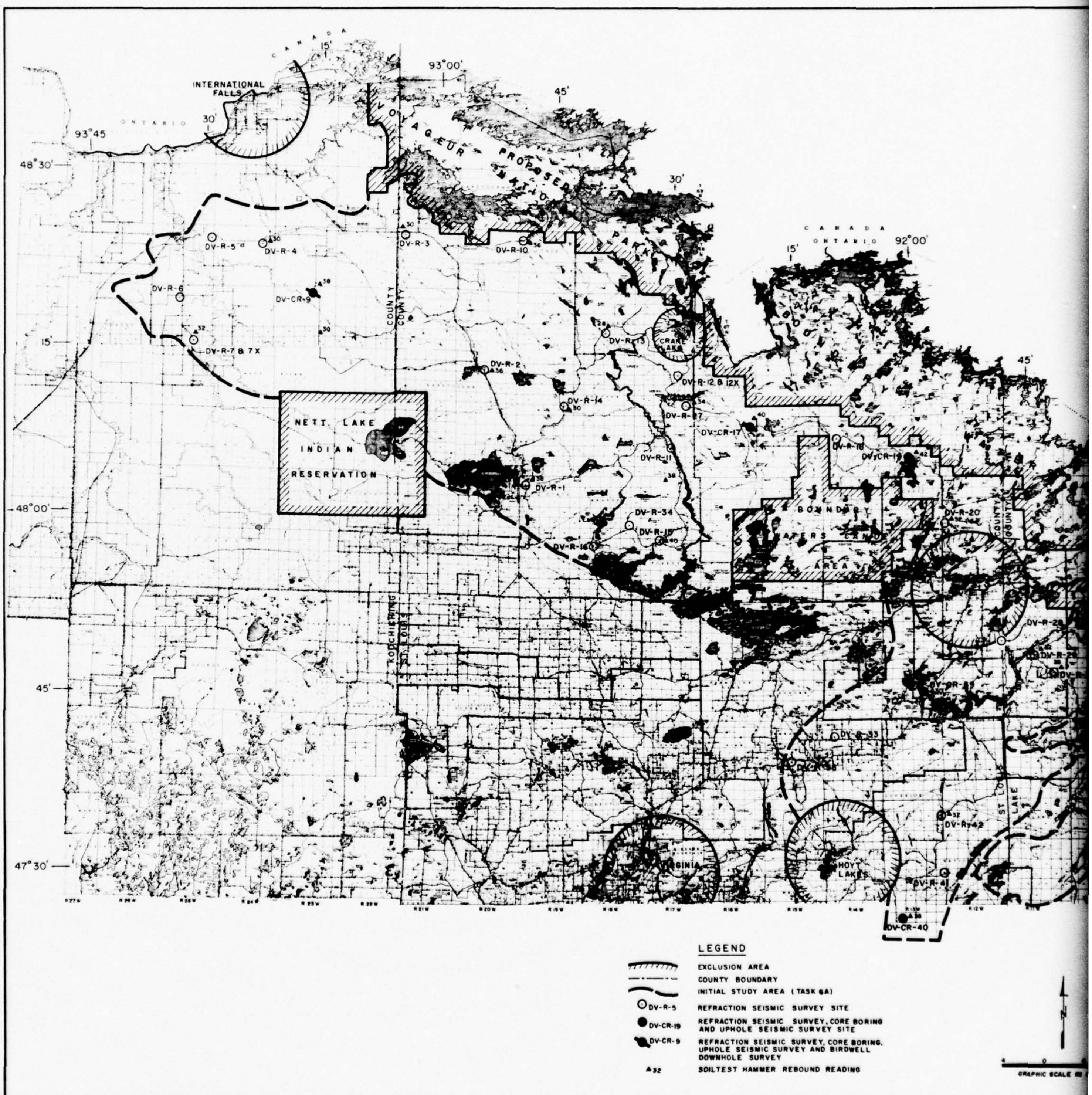


Figure 5.2 Field investigation sites.

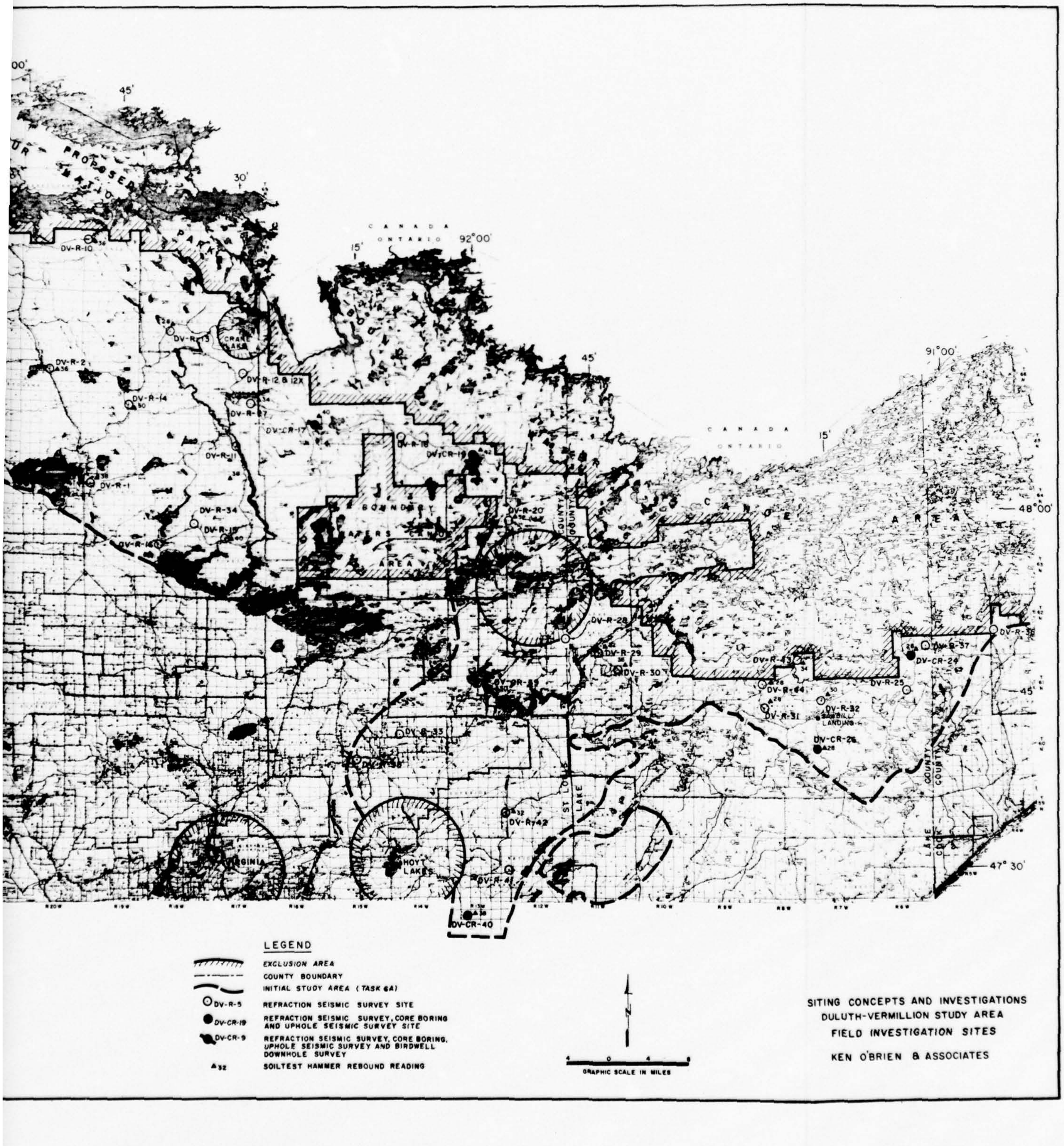


Figure 5.2 Field investigation sites.

APPENDIX A

DATA REPORT

Hole DV-CR-9

25 September 1969

Hole Location: Koochiching County, Minnesota

Longitude: 93° 15"

Latitude: 48° 20"

Township 67N, Range 23W, Section 3, NE 1/4 SE 1/4

Core

1. The following core was received on 8 September 1969 for testing:

Core Piece No.	Approximate Depth, ft
1	5
2	15
3	24
4	33
5	45
6	51
7	61
8	71
9	80
10	89
11	100
12	110
13	121
14	130
15	139
16	149
17	160
18	170
19	180
20	190
21	200

Description

2. The samples received were variable in appearance. According to the field log received with the core, the rock was identified as light-gray to medium-gray gneiss and pink to gray granite. Piece Nos. 3, 7, and 8 contained a few tightly closed macrofractures.

Quality and uniformity tests

3. To determine variations within the hole, specific gravity, Schmidt number, compressive strength, and compressional wave velocity were determined on specimens prepared from representative samples as given below:

Sample No.	Core Log Description	Core Depth	Sp Gr	Schmidt No.	Comp Strg, psi	Comp Wave Vel, fps
1	Granitic Gneiss	5	2.671	52.8	33,180	18,230
3	Gneiss	24	2.745	50.1	15,680	18,555
4	Banded Gneiss	33	2.774	--	13,850	18,820
7	**Granitic Gneiss** ~~Light-Gray Granite~~	61	2.676	--	22,850	18,300
8	Gneiss	71	2.755	38.6	18,700	17,630
9	Banded Gneiss	80	2.752	41.1	21,480	16,610
10	Banded Gneiss	89	2.765	35.5	14,360	17,540
12	Gneiss	110	2.774	50.8	14,060	17,820
13	**Granite** ~~Granitic Gneiss~~	121	2.650	51.6	26,210	18,705
16	Pink-Gray Granite	149	2.642	51.5	35,150	18,440
18	Gneiss	170	2.707	38.3	14,140	17,950
21	Gneiss	200	2.790	43.6	13,090	17,080
Average of Granitic Gneiss and Granites (4)			2.660	52.0	29,350	18,420
Average of Banded Gneiss and Gray Gneiss (8)			2.758	42.6	15,670	17,750

The Schmidt hammer test was not conducted on several specimens due to possibility of breakage. The results grouped conveniently into the two divisions shown which differed in compressive strength by a factor of 2.

Moduli of deformation

4. Representative specimens were selected for dynamic and static moduli of deformation tests. The dynamic moduli were determined by the proposed ASTM method for determination of ultrasonic pulse velocities and elastic constants of rock. The static moduli were computed from theory of elasticity by use of strain measurements taken from electrical resistance strain gages affixed to the specimens, Nos. 7, 9, 10, and 16. Stress-strain curves are given in plates 1, 2, 3, and 4. Specimens 7, 9, and 10 were cycled at 10,000 psi; specimen 16 was cycled at 20,000 psi. Results are given below.

Specimen No.	Modulus, psi x 10^6 Young's	Bulk	Shear	Shear Velocity, fps	Poisson's Ratio
		Dynamic Tests			
9	8.3	5.9	3.3	9395	0.26
10	8.6	7.0	3.3	9455	0.30
16	8.8	7.6	3.4	9750	0.31
		Static Tests			
7	10.4	7.8	4.1	--	0.29
9	8.5	4.9	3.5	--	0.20
10	9.5	4.9	4.0	--	0.18
16	10.6	5.7	4.5	--	0.19

All of the rock tested herein is apparently rather rigid material, exhibiting little hysteresis. The dynamic results were not included for specimen No. 7, which responded erratically to the dynamic test.

Conclusions

5. The core received from hole DV-CR-9 was identified by the field log received with the core as light- to medium-gray gneiss and pink to gray granite. A few tightly closed fractures were detected. Generally, the granitic material was considerably more competent than the remainder of the core, exhibiting an average compressive strength of nearly twice that yielded by the gray and banded gneiss. The granitic material also exhibited greater Schmidt numbers and compressive wave velocities. Banding appeared to have no effect on mode of failure, the banded specimens splitting through bands.

Property	Granite Gneiss and Granite	Banded Gneiss and Gray Gneiss
Specific Gravity	2.660	2.758
Schmidt Number	52.0	42.6
Compressive Strength, psi	29,350	15,670
Compressional Wave Velocity, fps	18,420	17,750
Young's Modulus, psi x 10^6	10.5	9.0

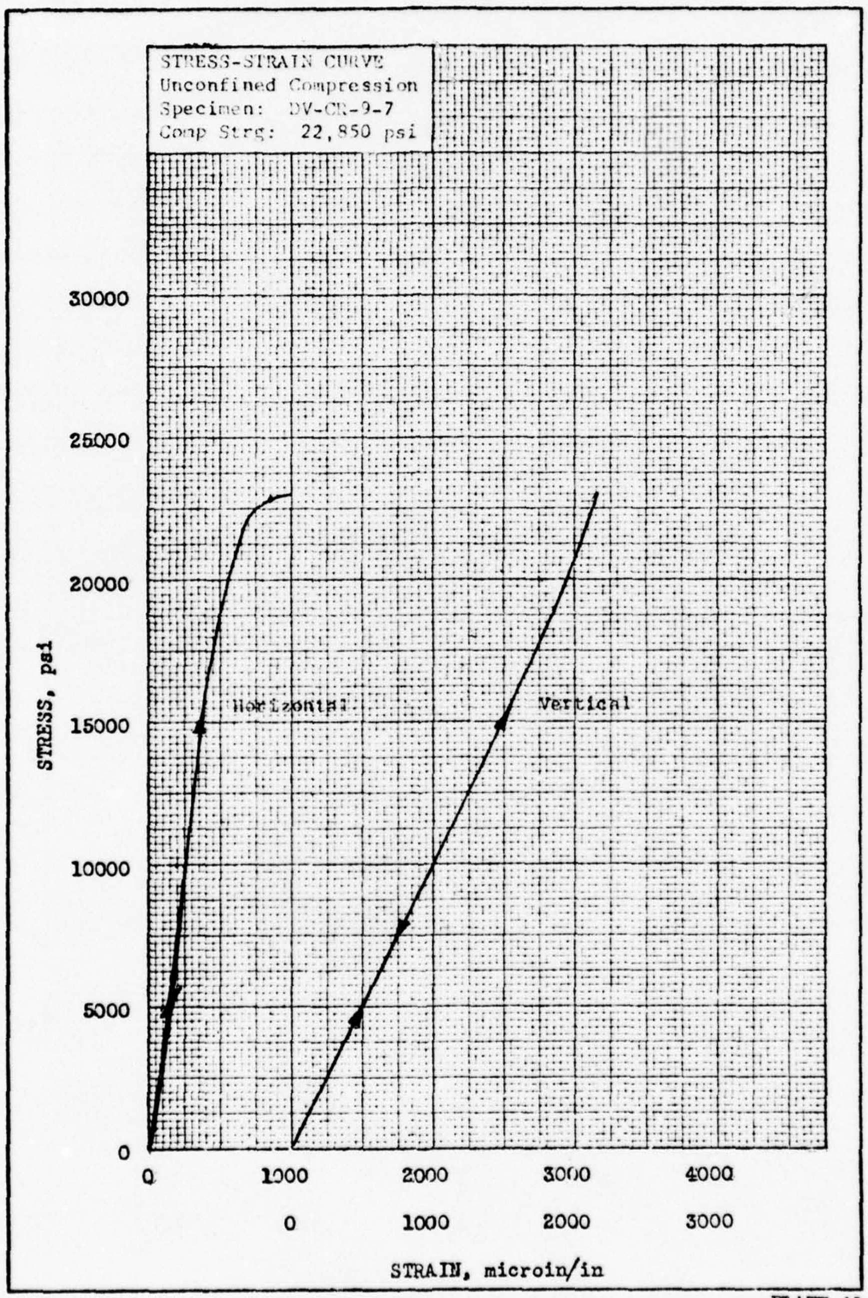

STRESS-STRAIN CURVE
Unconfined Compression
Specimen: DV-CR-9-7
Comp Strg: 22,850 psi
STRESS, psi
30000
25000
20000
15000
10000
5000
0
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
STRAIN, microin/in

PLATE A1

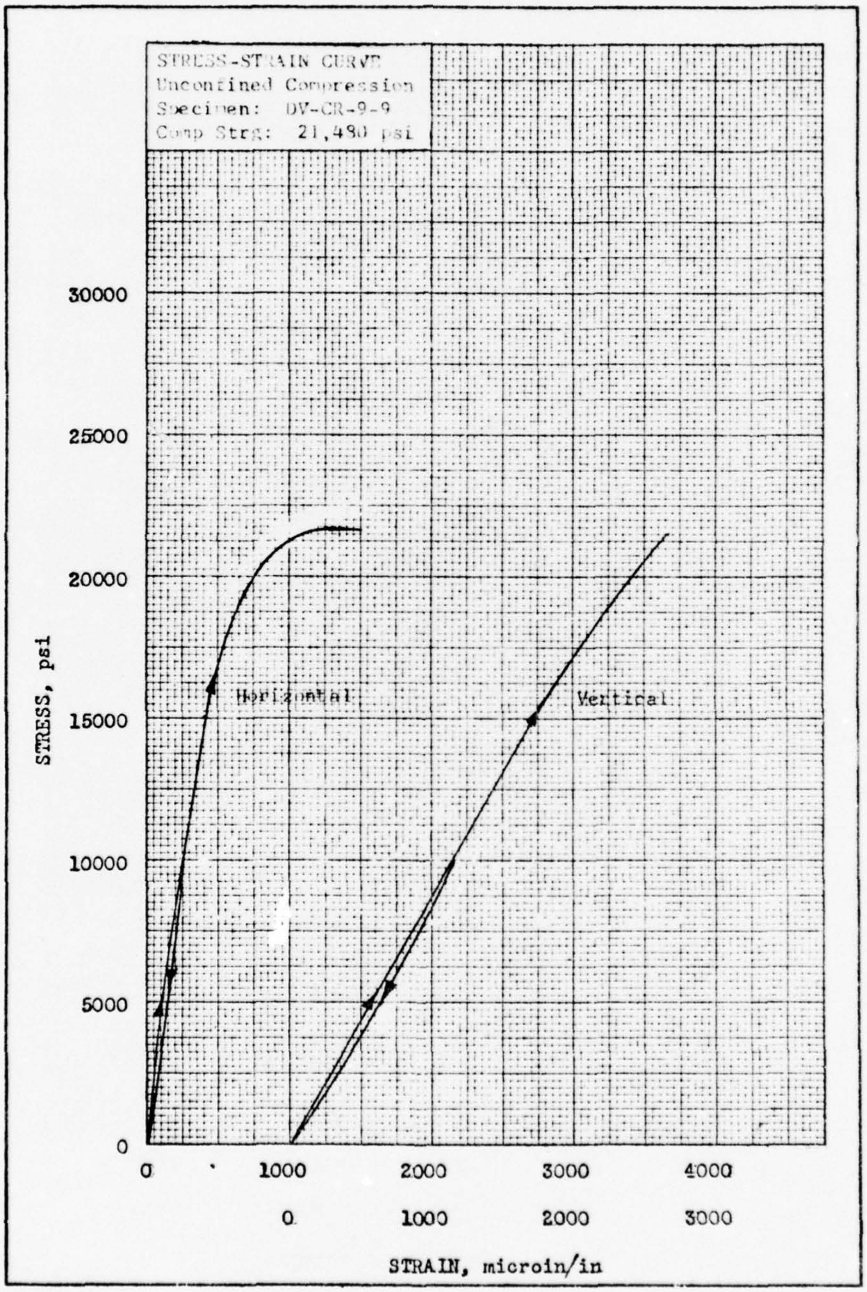

STRESS-STRAIN CURVE
Unconfined Compression
Specimen: DV-CR-9-9
Comp Strg: 21,480 psi
STRESS, psi
30000
25000
20000
15000
10000
5000
0
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
STRAIN, microin/in

PLATE A2

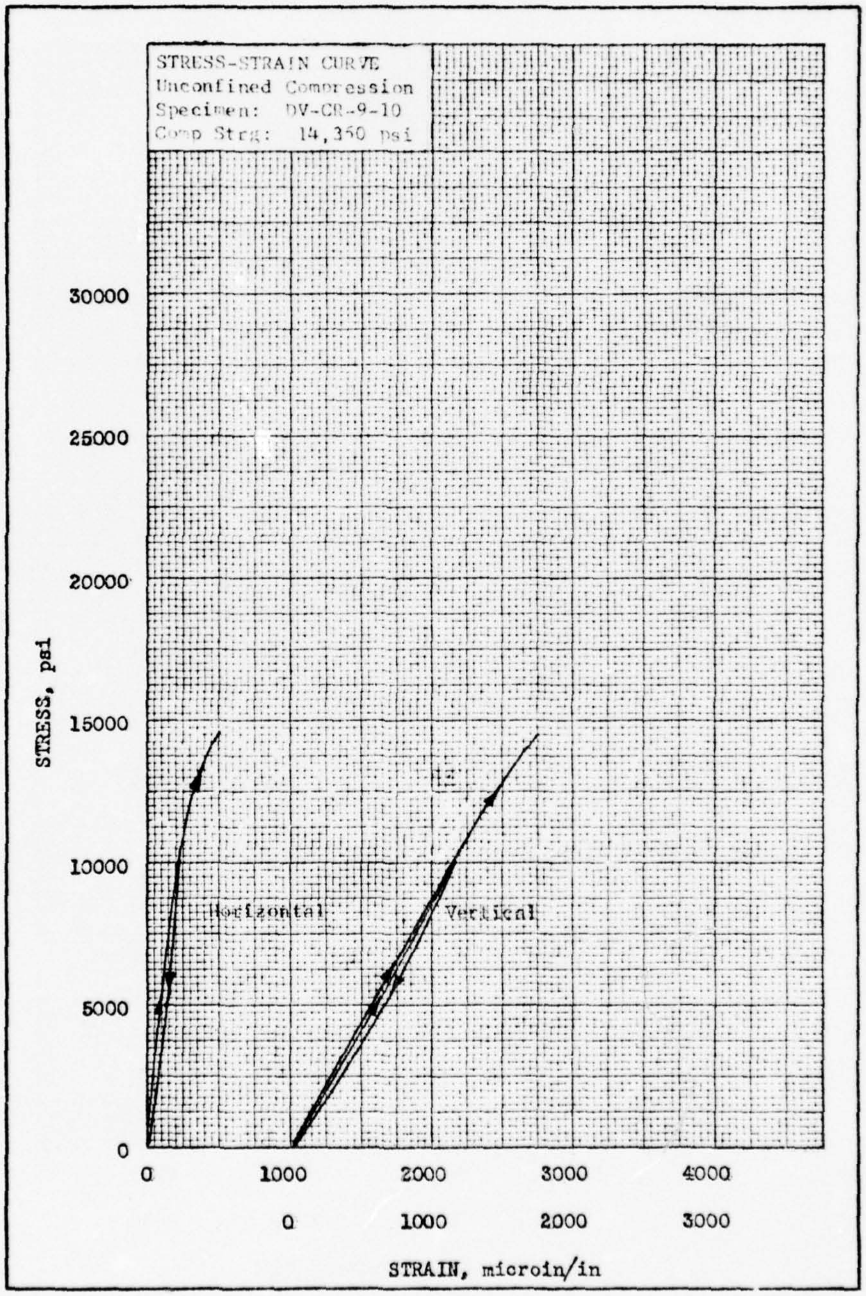
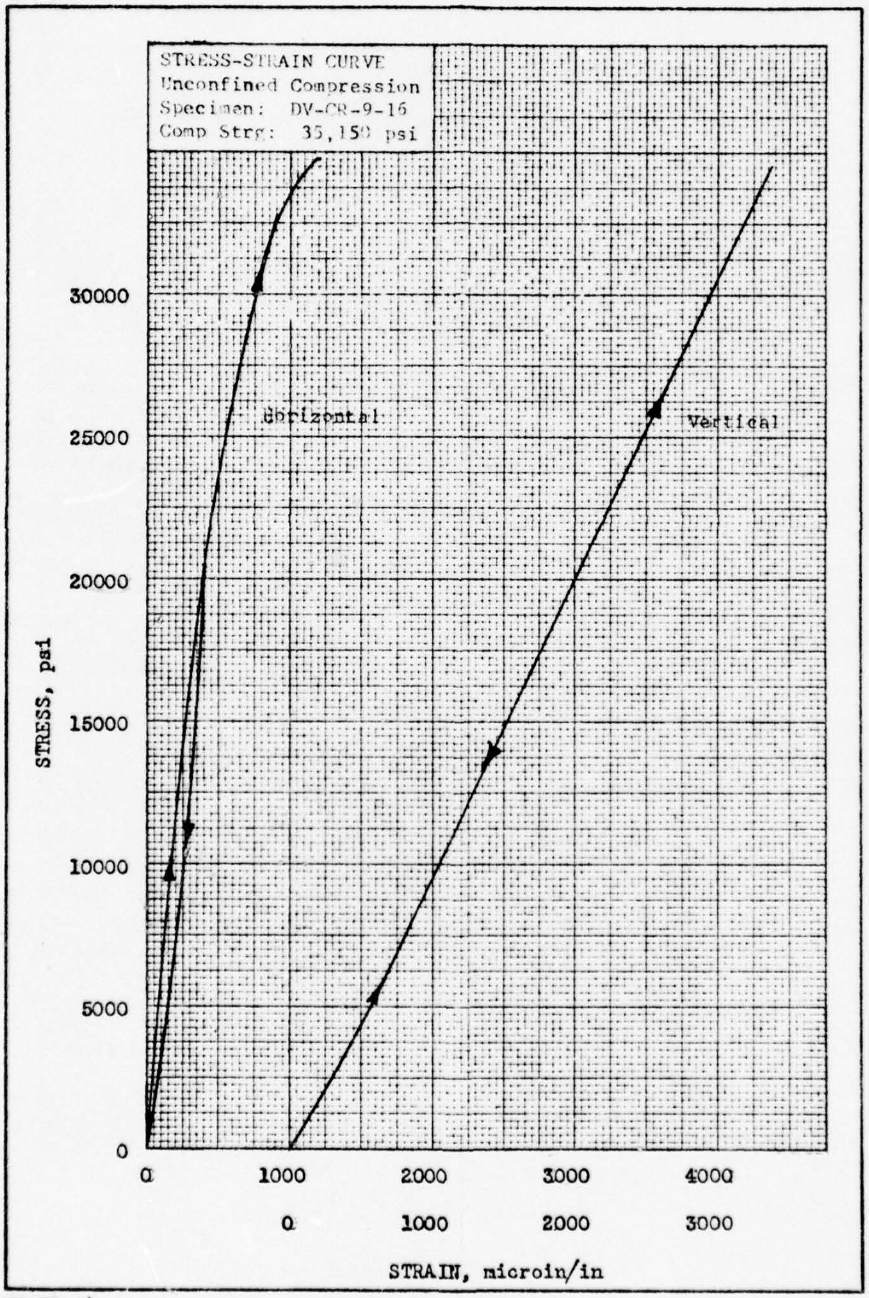

STRESS-STRAIN CURVE
Unconfined Compression
Specimen: DV-CR-9-10
Comp Strg: 14,350 psi
30000
25000
20000
15000
10000
5000
0
STRESS, psi
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
STRAIN, microin/in

PLATE A3



STRESS-STRAIN CURVE
Unconfined Compression
Specimen: DV-CR-9-16
Comp Strg: 35,150 psi
Horizontal
Vertical
STRESS, psi
30000
25000
20000
15000
10000
5000
0
0
1000
2000
3000
4000
0
1000
2000
3000
STRAIN, microin/in

PLATE A4

APPENDIX B

DATA REPORT

Hole DV-CR-17

22 September 1969

Hole Location: St. Louis County, Minnesota

Longitude: 92° 27' 48" West

Latitude: 48° 07' 55" North

Township 65N, Range 16W, Section 12

1100' S/NL, 800' E/WL, NW 1/4 NW 1/4

Core

1. The following core was received on 8 September 1969 for testing:

Core Piece No.	Approximate Depth, ft
1	4
2	15
3	25
4	36
5	46
6	54
7	65
8	76
9	85
10	97
11	109
12	116
13	127
14	137
15	146
16	156
17	161
18	170
19	178
20	182
21	190
22	198

Description

2. The samples received were gray-colored rock identified as granite by the field log received with the core. Piece Nos. 1, 2, 5, 6, 13, 15, 18, 20, and 21 appeared to be coarse grained and the remainder of the specimens medium grained. The core received was very uniform in appearance throughout the entire depth.

Quality and uniformity tests

3. To determine variations within the hole, specific gravity, Schmidt number, compressive strength, and compressional wave velocity were determined on specimens prepared from representative samples as given below:

	Sample No.	Description	Core Depth	Sp Gr	Schmidt No.	Comp Strg, psi	Comp Wave Vel, fps
	1	Coarse grained	4	2.662	48.4	17,520	15,260
	2	Coarse grained	15	2.636	50.7	18,580	15,930
	4	Med. to coarse ~~Med.~~ grained	36	2.658	49.8	14,180	15,500
Tonalite	6	Coarse grained	54	2.642	48.8	10,500	15,390
	11	Med. to coarse ~~Med.~~ grained	109	2.715	47.6	19,970	16,110
	17	Med. to coarse ~~Med.~~ grained	161	2.664	48.2	11,820	13,730
	18	Coarse grained	170	2.647	49.7	14,780	15,590
	Average all specimens			2.660	49.0	15,340	15,360

The test results verify the visual observation of a relatively uniform material throughout the depth sampled. The results also indicate that the rock would be classified, at best, as medium hard or average in terms of hard rock terminology. A typical hard rock could be expected to yield strengths and velocities approximately 20-30 percent higher than those determined for hole DV-CR-17.

Moduli of deformation

4. Representative specimens were selected for dynamic and static moduli of deformation tests. The dynamic moduli were determined by the proposed ASTM method for determination of ultrasonic pulse velocities and elastic constants of rock. The static moduli were computed from theory of elasticity by use of strain measurements taken from electrical resistance strain gages affixed to the specimens, Nos. 1 and 11. Stress-strain curves are given in plates 1 and 2. Results are given below.

Specimen No.	Modulus, psi x 10^6 Young's	Bulk	Shear	Shear Velocity, fps	Poisson's Ratio
		Dynamic Tests			
1	8.6	2.5	4.6	11,340	*
11	6.9	1.8	4.0	10,460	*
		Static Tests			
1	11.0	9.2	4.2	--	0.30
11	11.0	*	*	--	*

* Could not be determined.

Some crack closure is indicated by the initial reverse curvature of the stress-strain curves. Little hysteresis is evident, however. The static moduli were computed at approximately one-half of the ultimate strength, resulting in higher values compared to the dynamic moduli which were determined at low stress levels before the cracks were closed.

Conclusions

5. The core received from hole DV-CR-17 was gray-colored rock identified as granite by the field log received with the samples. The core was very uniform in appearance ranging from medium to coarse grained. No macrofacturing was noted; however, some crack closure was indicated on the stress-strain curves. The test results verified the uniformity of the core, but indicated the material would probably be classified only as average in hard rock terminology.

Property	Result
Specific gravity	2.660
Schmidt number	49.0
Compressive strength, psi	15,340
Compressional wave velocity, fps	15,360
Static Young's modulus, psi x 10^6	7.0-11.0

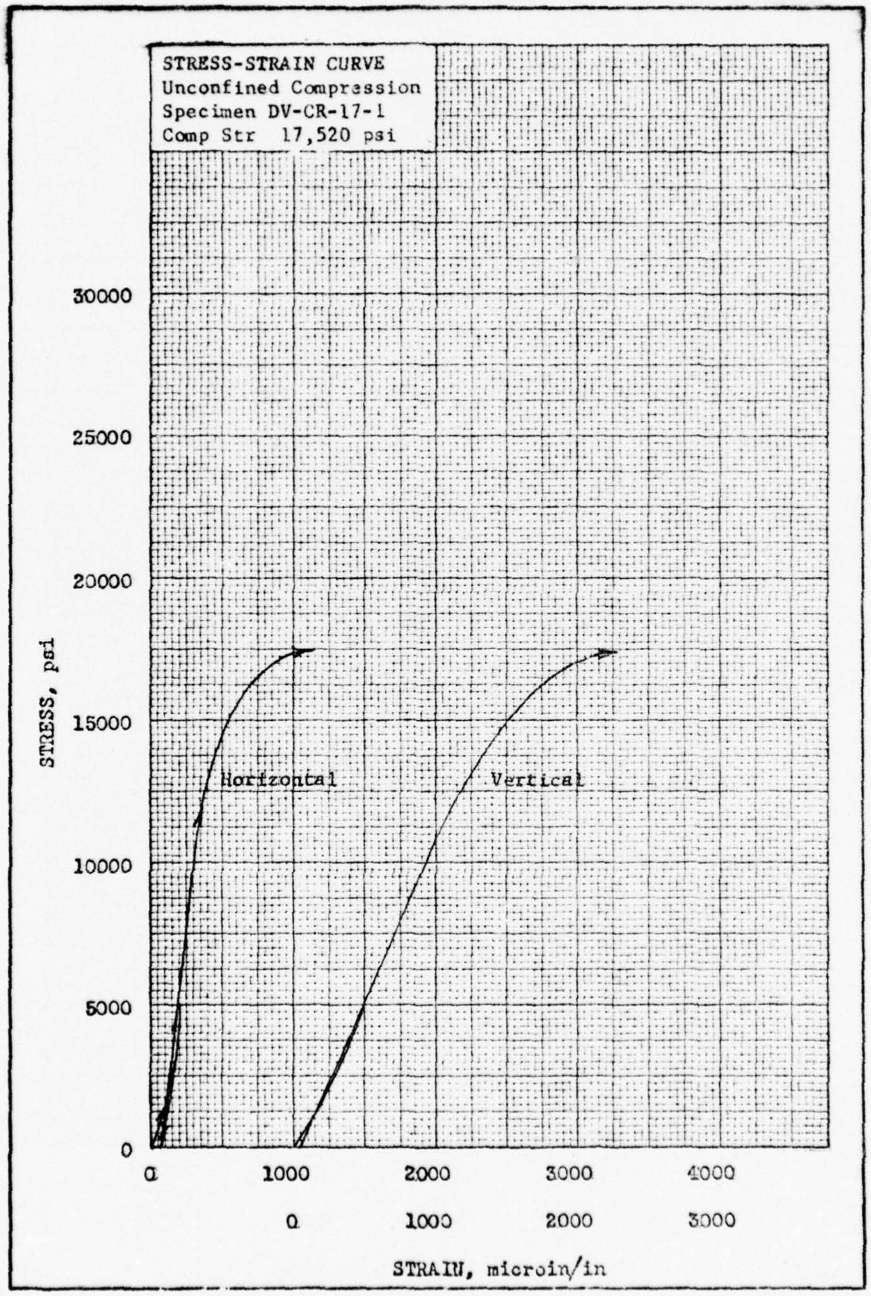
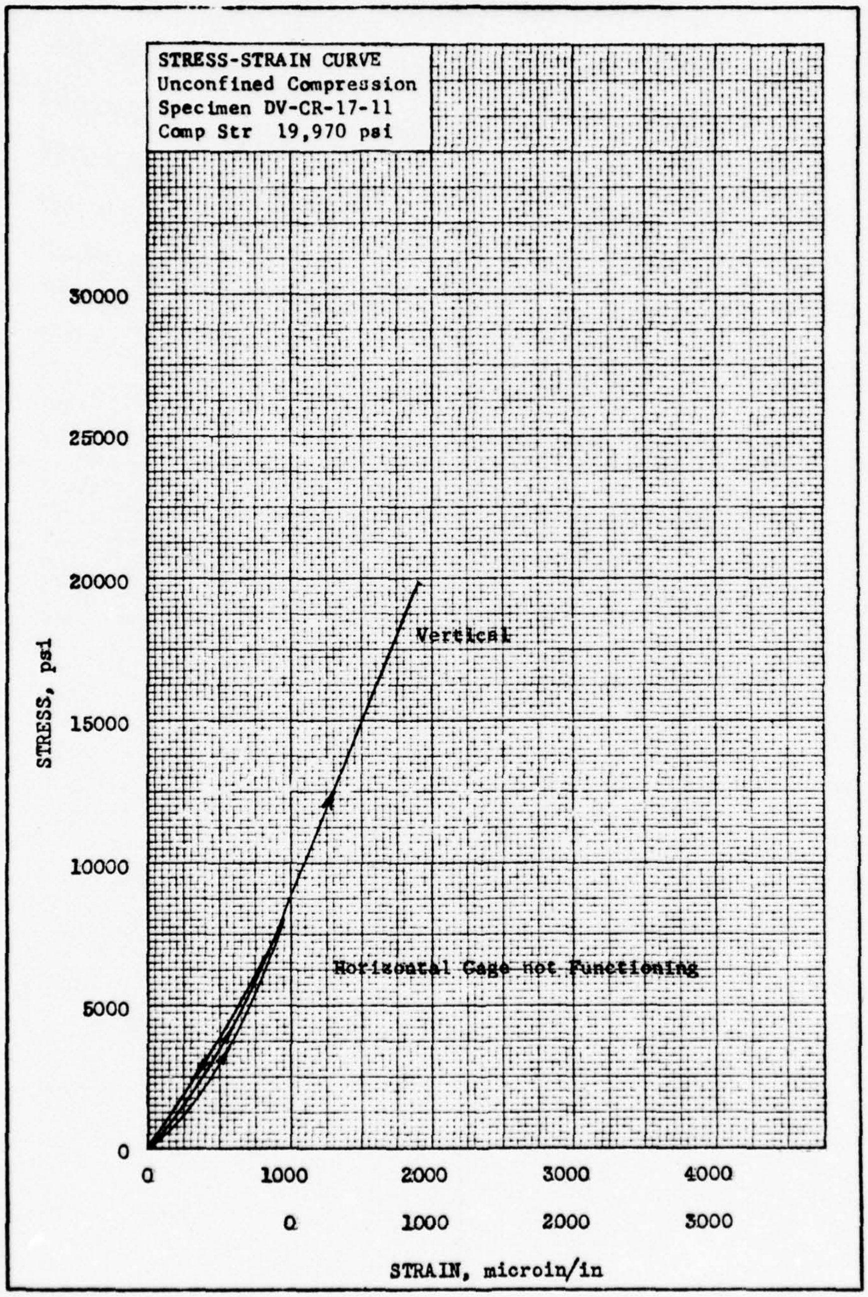

STRESS-STRAIN CURVE
Unconfined Compression
Specimen DV-CR-17-1
Comp Str 17,520 psi
30000
25000
20000
15000
10000
5000
0
STRESS, psi
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
STRAIN, microin/in

PLATE B1



STRESS-STRAIN CURVE
Unconfined Compression
Specimen DV-CR-17-11
Comp Str 19,970 psi
STRESS, psi
30000
25000
20000
15000
10000
5000
0
Vertical
Horizontal Gage not Functioning
0
1000
2000
3000
4000
0
1000
2000
3000
STRAIN, microin/in

PLATE B2

APPENDIX C

DATA REPORT

Hole DV-CR-19

30 September 1969

Hole Location: St. Louis County, Minnesota

Township 65N, Range 13W, Section 21

Longitude: 91° 59' 46"

Latitude: 48° 05' 43"

220' W/EL, 620' N/SL, SE 1/4 SE 1/4

Core

1. The following core was received on 17 September 1969 for testing:

Core Piece No.	Approximate Depth, ft
1	9
2	17
3	28
4	37
5	46
6	57
7	68
8	77
9	87
10	97
11	100
12	110
13	119
14	129
15	140
16	150
17	159
18	170
19	180
20	185
21	191
22	200

Description

2. The samples received were quite uniform in appearance. According to the field log received with the core, the rock was identified as pink, medium- to coarse-grained granite.

Quality and uniformity tests

3. To determine variations within the hole, specific gravity, Schmidt number, compressive strength, and compressional wave velocity were determined on specimens prepared from representative samples as given below:

	Sample No.	Description	Core Depth	Sp Gr	Schmidt No.	Comp Strg, psi	Comp Wave Vel, fps
	2	Intact Granite	47	2.639	49.7	34,390	16,970
	5	Granite w/High-Angle Fracture*	46	2.647	50.1	23,940	16,325
	8	Intact Granite	77	2.643	53.5	32,580	17,225
Medium-grained tonalite	11	Intact Granite	100	2.638	49.2	36,520	16,020
	12	Intact Granite	110	2.640	53.1	36,140	16,530
	15	Intact Granite	140	2.648	53.1	36,210	16,755
	18	Intact Granite	170	2.656	49.8	40,300	16,110
	21	Intact Granite	191	2.639	50.0	35,610	16,145
Average of Intact Specimens (7)				2.643	51.2	35,960	16,535
Specimen with High-Angle Fracture				2.647	50.1	23,940	16,325

* Specimen discovered to have healed, high-angle fracture which may have initiated failure.

4. The material tested exhibited very uniform physical characteristics throughout the depth of the hole, the only appreciable deviation being the somewhat lower compressive strength yielded by the specimen containing the healed, high-angle fracture.

Moduli of deformation

5. Representative specimens were selected for dynamic and static moduli of deformation tests. The dynamic moduli were determined by the proposed ASTM method for determination of ultrasonic pulse velocities and elastic constants of rock. The static moduli were computed from theory of elasticity by use of strain measurements taken from electrical resistance strain gages affixed to the specimens, Nos. 8, 11, and 18. Stress-strain curves are given in plates 1, 2, and 3. All three specimens were cycled at 20,000 psi. Results are given below.

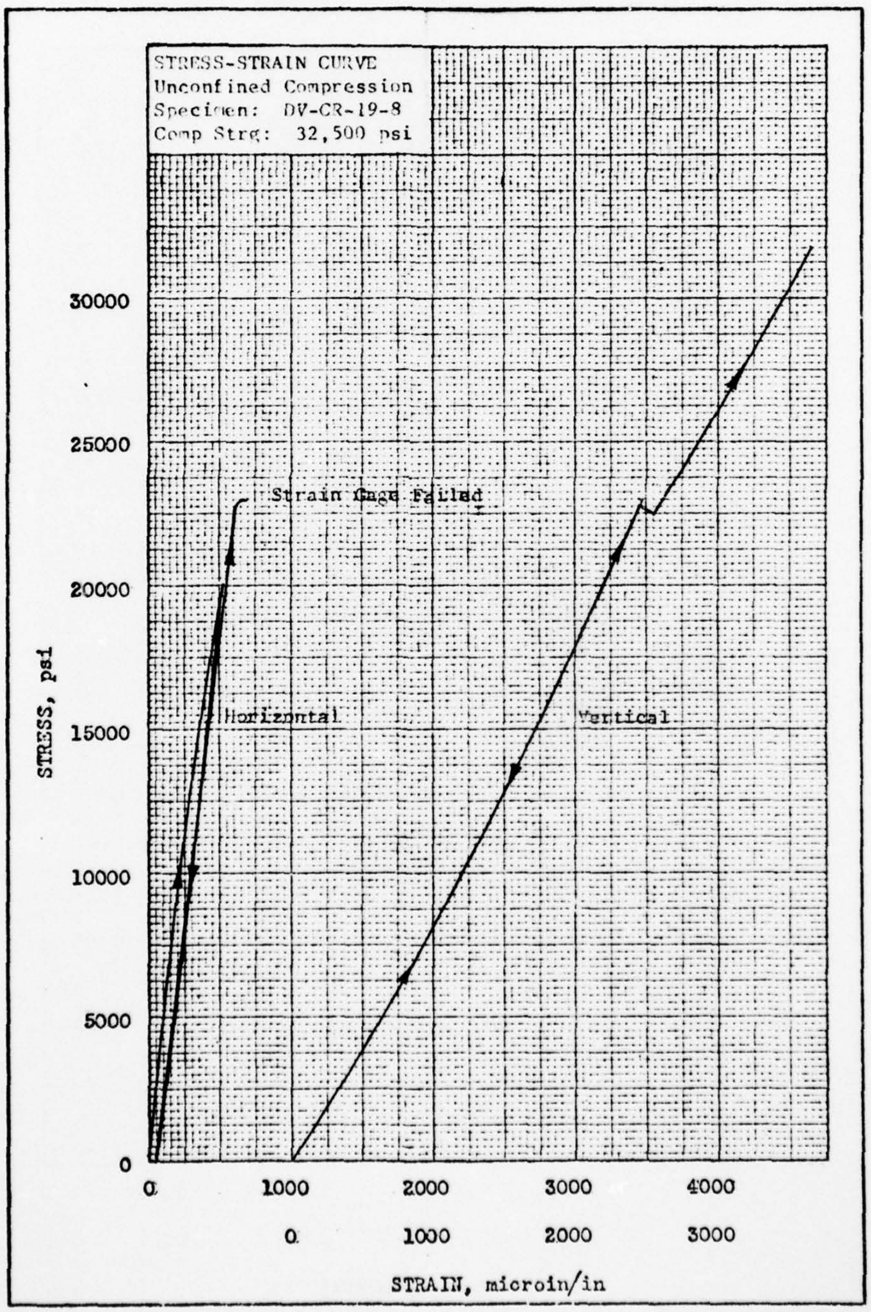
Specimen No.	Modulus, psi x 10^6 Young's	Modulus, psi x 10^6 Bulk	Modulus, psi x 10^6 Shear	Shear Velocity, fps	Poisson's Ratio
		Dynamic Tests			
8	8.0	6.4	3.1	9340	0.29
11	7.5	5.2	3.0	9155	0.26
18	7.5	5.3	3.0	9125	0.26
		Static Tests			
8	10.0	7.2	3.9	--	0.27
11	9.6	5.6	4.0	--	0.22
18	10.2	5.5	4.3	--	0.19

6. All of the rock tested herein is apparently rather rigid material, exhibiting little hysteresis. The slight initial reverse curvature of the stress-strain curves did, however, indicate a small amount of initial crack closure. Static moduli were computed at approximately one-half the ultimate strength, resulting in slightly higher values than yielded by dynamic tests which were conducted at lower stress levels before crack closure.

Conclusions

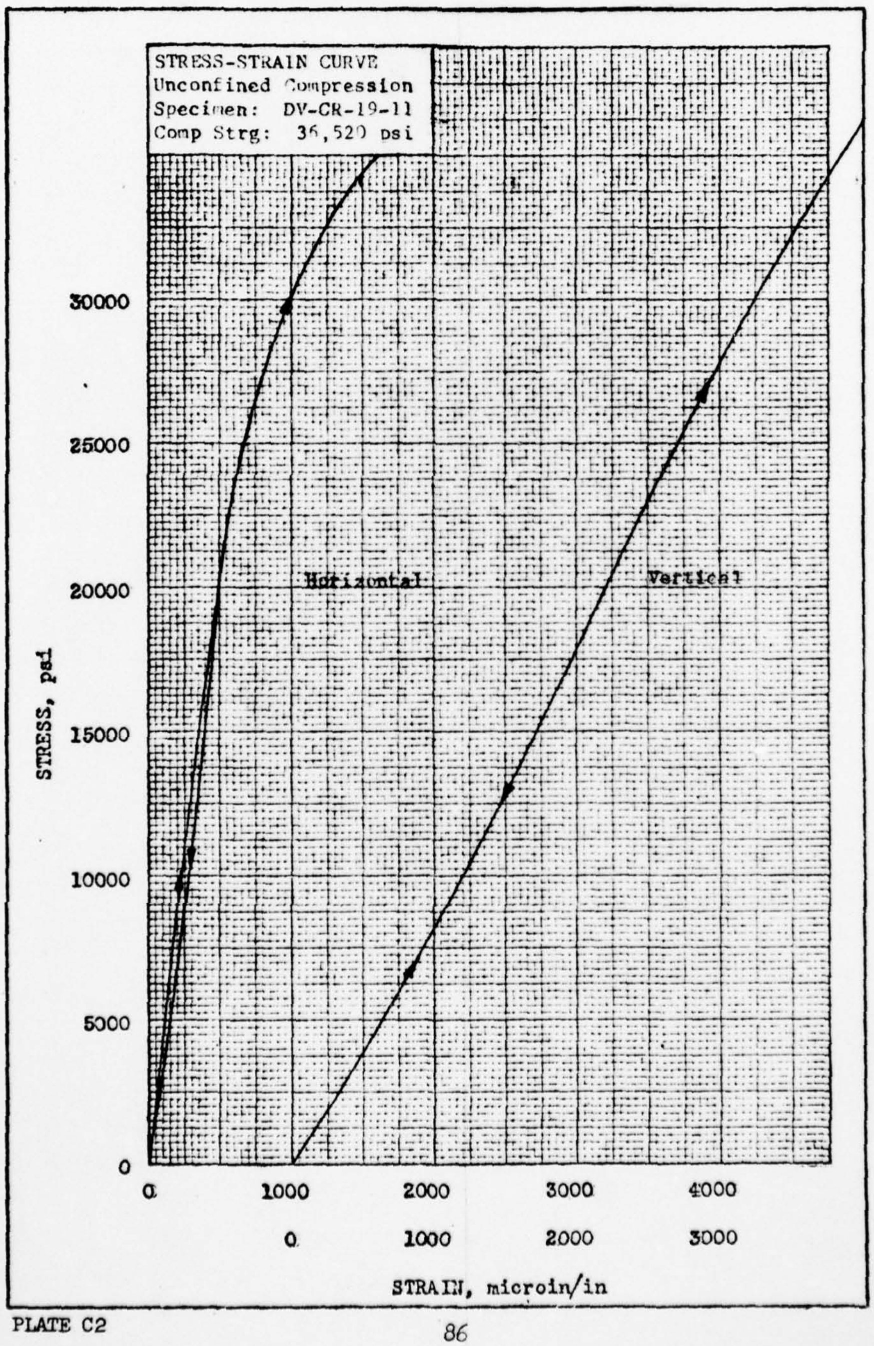
7. The core received from hole DV-CR-19 was pink, medium- to coarse-grained rock identified as granite by the field log received with the core. The material was unusually uniform, both in appearance and physical characteristics, the only deviation from this uniformity being one somewhat lower compressive strength exhibited by a specimen containing a healed, high-angle fracture. Generally, the samples from this hole could be described as representing very competent rock.

Property	Intact Specimens	Fractured Specimen
Specific Gravity	2.643	2.647
Schmidt Number	51.2	50.1
Compressive Strength, psi	35,960	23,940
Compressional Wave Velocity, fps	15,535	16,325
Static Young's Modulus, psi $\times 10^6$	9.9	--



STRESS-STRAIN CURVE
Unconfined Compression
Specimen: DV-CR-19-8
Comp Strg: 32,500 psi
Strain Gage Failed
Horizontal
Vertical
STRESS, psi
0
5000
10000
15000
20000
25000
30000
0
1000
2000
3000
4000
0
1000
2000
3000
STRAIN, microin/in

PLATE C1



STRESS-STRAIN CURVE
Unconfined Compression
Specimen: DV-CR-19-11
Comp Strg: 36,520 psi
STRESS, psi
30000
25000
20000
15000
10000
5000
0
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
STRAIN, microin/in

PLATE C2

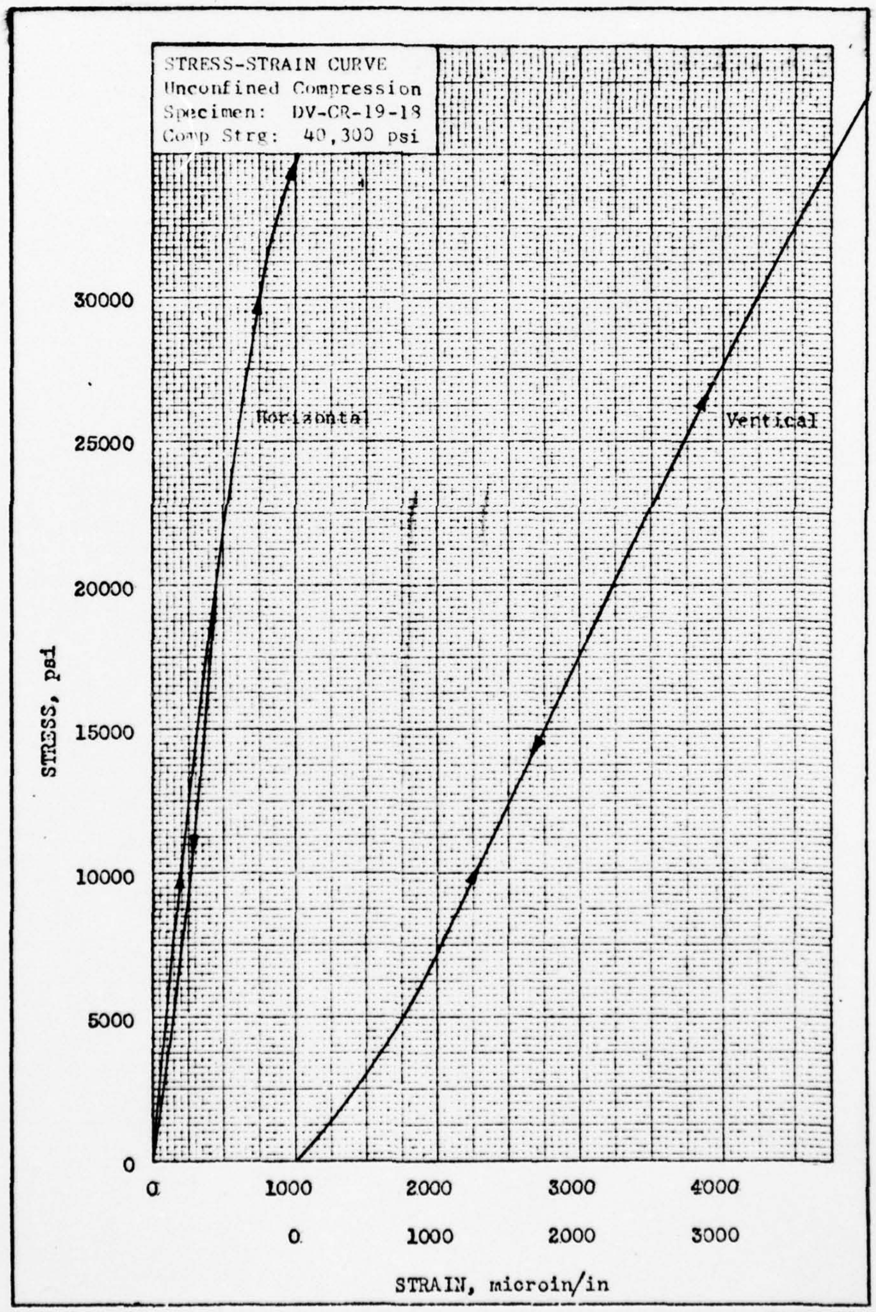

STRESS-STRAIN CURVE
Unconfined Compression
Specimen: DV-CR-19-18
Comp Strg: 40,300 psi
Horizontal
Vertical
STRESS, psi
30000
25000
20000
15000
10000
5000
0
0
1000
2000
3000
4000
0
1000
2000
3000
STRAIN, microin/in

PLATE C3

APPENDIX D

DATA REPORT

Hole DV-CR-24

8 October 1969

Hole Location: Lake County, Minnesota

Township 61N, Range 6W, Section 3, NE 1/4 NE 1/4

Longitude: 91° 04' 02" West

Latitude: 47° 47' 45" North

Core

1. The following core was received on 2 October 1969 for testing:

Core Piece No.	Approximate Depth, ft
1	5
2	16
3	25
4	35
5	45
6	55
7	66
8	74
9	85
10	88
11	95
12	106
13	114
14	124
15	135
16	146
17	156
18	165
19	176
20	185
21	195
22	197

Description

2. The samples received were quite uniform in appearance. According to the field log received with the core, the rock was identified as medium- to dark-gray, coarse-grained gabbro. Specimen Nos. 2, 5, and 11 contained tightly closed incipient fractures.

Quality and uniformity tests

3. To determine variations within the hole, specific gravity, Schmidt number, compressive strength, and compressional wave velocity were determined on specimens prepared from representative samples as given below:

	Sample No.	Description	Core Depth	Sp Gr	Schmidt No.*	Comp Strg, psi	Comp Wave Vel, fps
	1	Intact	5	2.852	--	29,640	18,540
	2	Contained Incipient Fracture	16	2.875	57.3	24,000	21,575
	5	Contained Incipient Fracture	45	2.811	--	24,150	20,300
Fractured coarse-grained gabbro	9	Intact	85	2.878	56.4	24,590	18,655
	11	Contained Incipient Fracture	95	3.019	59.3	27,000	21,575
	14	Intact	124	2.836	--	14,700	21,050
	18	Intact	165	2.848	55.3	8,640	20,345
	22	Intact	197	2.856	57.6	23,090	19,770
	Average of All Specimens			2.872	57.2	21,980	20,225

* Schmidt hammer test not conducted on several specimens due to possibility of breakage.

4. The apparent uniform nature of the core was not substantiated by the test results. Sample No. 11 contained a fracture, but the results indicated it was one of the more competent specimens. Conversely, specimen No. 18, in which no fracturing was observed, yielded a compressive strength of only 8640 psi. Obviously the fracturing observed prior to testing was not an influencing factor in the results.

Moduli of deformation

5. Representative specimens were selected for dynamic and static moduli of deformation tests. The dynamic moduli were determined by the proposed ASTM method for determination of ultrasonic pulse velocities and elastic constants of rock. The static moduli were computed from theory of elasticity by use of strain measurements taken from electrical resistance strain gages affixed to the specimens, Nos. 2 and 9. Stress-strain curves are given in plates 1 and 2. Specimen 2 was cycled at 10,000 psi, and specimen 9 was cycled at 20,000 psi. Results are given below.

Specimen No.	Modulus, psi x 10^6 Young's	Bulk	Shear	Shear Velocity, fps	Poisson's Ratio
		Dynamic Tests			
2	11.5	12.2	4.3	10,555	0.34
9	9.9	9.0	3.4	9,330	0.33
		Static Tests			
2	5.5	3.3	2.9	--	0.22
9	6.8	4.7	2.7	--	0.26

All of the rock tested herein is apparently rather rigid material, exhibiting some hysteresis. The slight initial reverse curvature of the stress-strain curves did, however, indicate a small amount of initial crack closure.

Conclusions

6. The core received from hole DV-CR-24 was identified as medium- to dark-gray, coarse-grained gabbro by the field log received with the core. The core was uniform in appearance, but physical test results were rather variable. Compressive wave velocities ranged from 18,500 to 21,500 fps, specific gravities from 2.81 to 3.02, and compressive strengths from 8600 to 29,600 psi. Macrofracturing in several specimens had no apparent detrimental effect on compressive strength.

Property	All Specimens
Specific Gravity	2.872
Schmidt Number	57.2
Compressive Strength, psi	21,980
Compressional Wave Velocity, fps	20,225
Static Young's Modulus, psi x 10^6	6.2

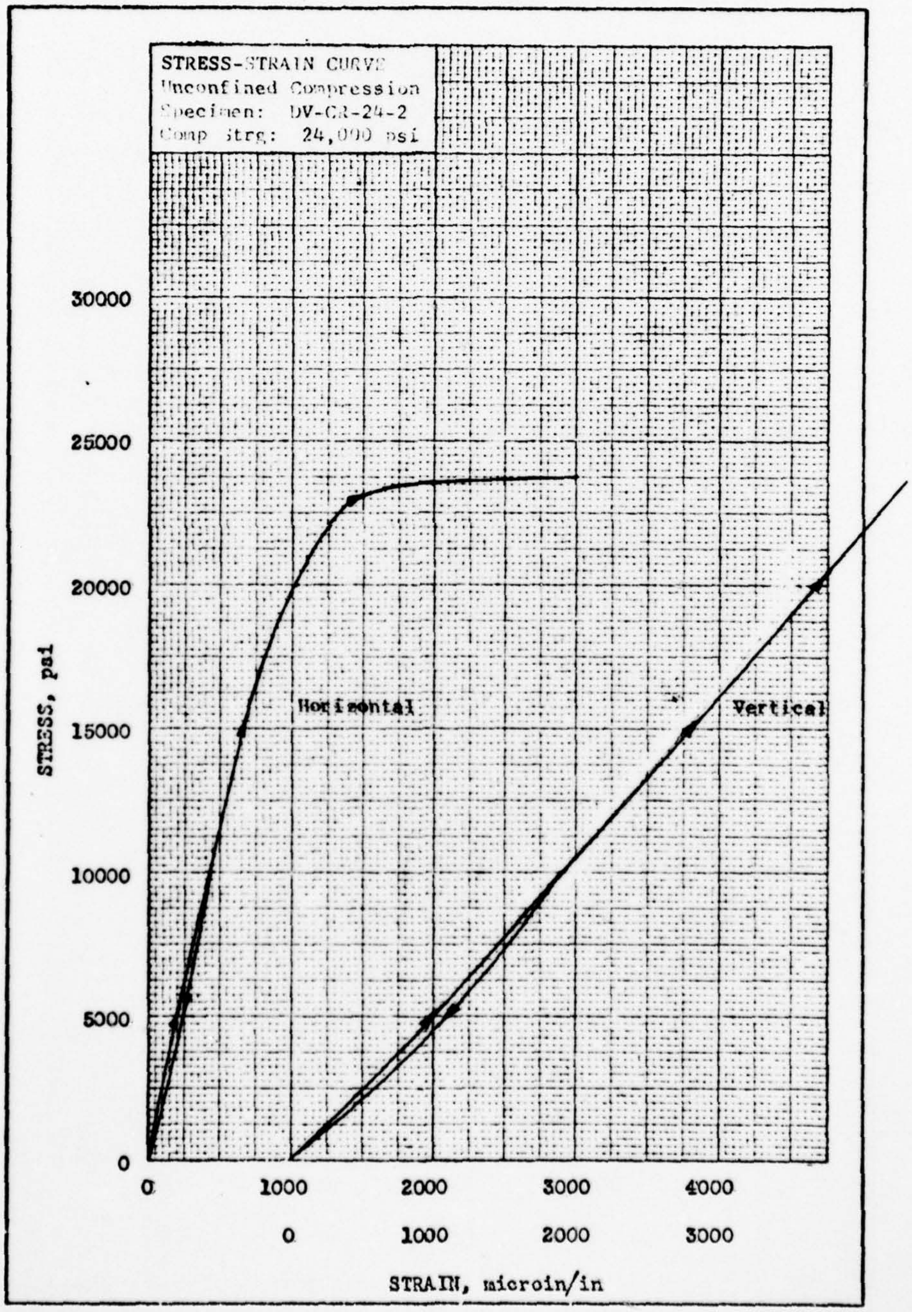
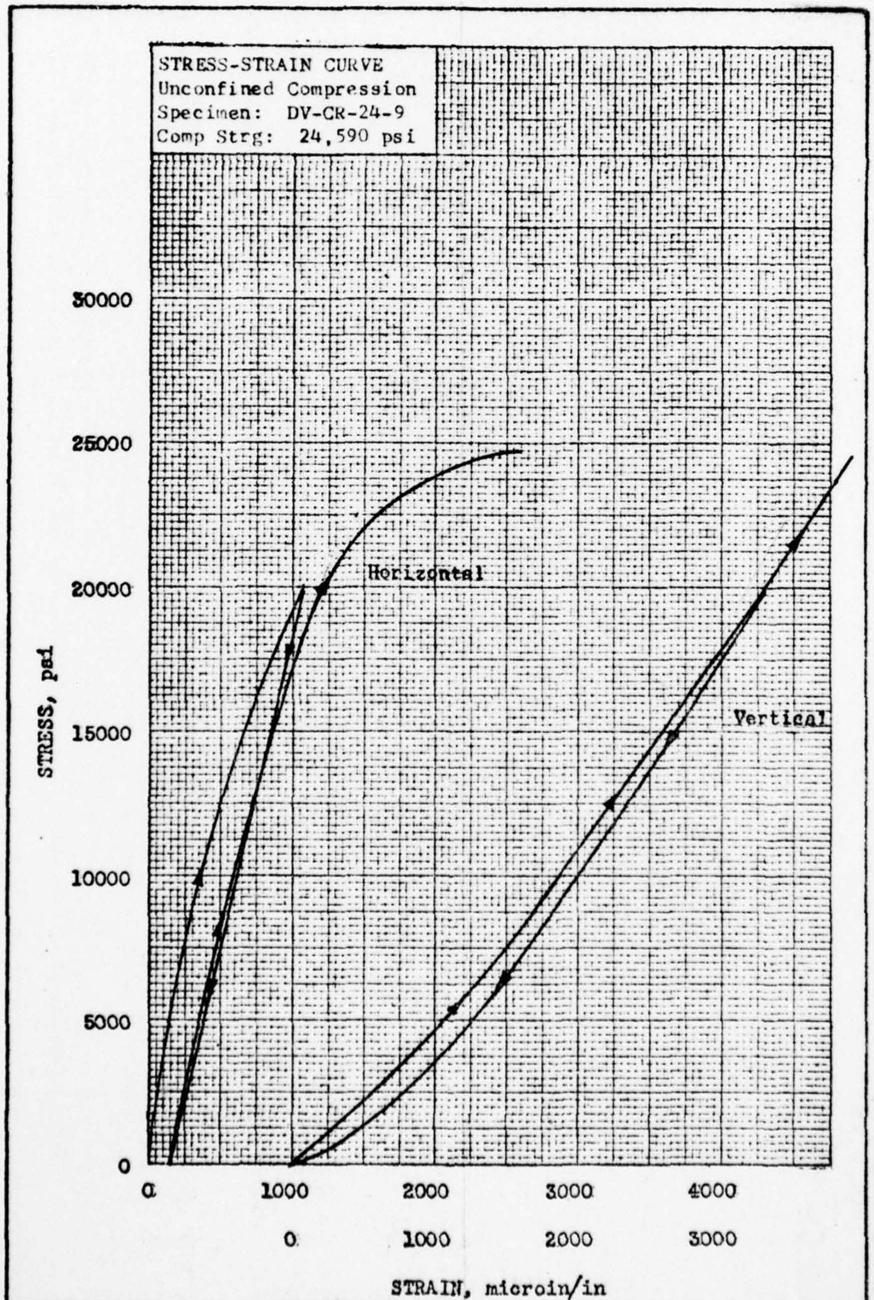

STRESS-STRAIN CURVE
Unconfined Compression
Specimen: DV-CR-24-2
Comp Strg: 24,000 psi
STRESS, psi
30000
25000
20000
15000
10000
5000
0
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
STRAIN, microin/in

PLATE D1


STRESS-STRAIN CURVE
Unconfined Compression
Specimen: DV-CR-24-9
Comp Strg: 24,590 psi
Horizontal
Vertical
STRESS, psi
0
5000
10000
15000
20000
25000
30000
0
1000
2000
3000
4000
0
1000
2000
3000
STRAIN, microin/in
PLATE D2

APPENDIX E

DATA REPORT

Hole DV-CR-39

1 October 1969

Hole Location: St. Louis County, Minnesota

Township 61N, Range 13W, Section 23, SW 1/4 NW 1/4

Longitude: 91° 58' 15" West

Latitude: 47° 45' 03" North

Core

1. The following core was received on 22 September 1969 for testing:

Core Piece No.	Approximate Depth, ft
1	8
2	21
3	31
4	42
5	51
6	60
7	70
8	80
9	89
10	100
11	111
12	121
13	127
14	134
15	144
16	154
17	166
18	175
19	184
20	190
21	200

Description

2. The samples received were quite variable in appearance. According to the field log received with the core, the rock was identified as migmetite, gray to greenish-gray gneiss, and gray to pink granite. All pieces contained seams, bands, and/or fractures, some of which were inclined at critical angles. Some of the fractures were healed; some were incipient.

Quality and uniformity tests

3. To determine variations within the hole, specific gravity, Schmidt number, compressive strength, and compressional wave velocity were determined on specimens prepared from representative samples as given below:

	Sample No.	Description	Core Depth	Sp Gr	Schmidt No.	Comp Strg, psi	Comp Wave Vel, fps
Medium-grained tonalite	2	~~Gray Granite~~ with Vertical Fracture	21	2.569	54.0	30,300	18,805
Amphibolite	4	~~Gneiss~~, Critical-Angle Healed Fracture	42	2.870	52.1	15,240	21,120
Amphibolite	7	~~Gneiss~~, Critical-Angle Healed Fracture	70	2.878	47.6	5,920	19,820
Amphibolite	8	~~Gneiss~~, High-Angle Healed Fracture	80	2.883	51.2	21,520	21,090
Medium-grained tonalite	11	~~Granite-Gneiss~~ Contact	111	2.727	50.2	15,210	18,670
Amphibolite	13	~~Gneiss~~, High-Angle Healed Fracture	127	2.829	51.5	22,970	21,800
Medium-grained tonalite	15	~~Granite-Gneiss~~ Contact	144	2.777	50.9	15,030	20,500
Medium-grained tonalite	18	~~Granite~~ with High-Angle Band	175	2.581	55.2	13,150	19,720
Amphibolite	19	~~Gneiss~~, High-Angle Healed Fracture	184	2.822	54.1	23,790	21,000
Medium-grained tonalite	20	~~Granite~~ with High-Angle Band	190	2.658	56.3	24,520	19,150
	Average of Specimens with Contacts and Bands (4)			2.711	53.2	16,980	19,510
	Average of Specimens with Vertical and High-Angle Fractures (4)			2.801	52.7	24,640	20,675
	Average of Specimens with Critical-Angle Fractures (2)			2.874	49.8	11,080	20,470

Apparently the critical-angle fractures and the contacts and bands all detrimentally affect the compressive strength but not the other properties.

Moduli of deformation

4. Representative specimens were selected for dynamic and static moduli of deformation tests. The dynamic moduli were determined by the proposed ASTM method for determination of ultrasonic pulse velocities and elastic constants of rock. The static moduli were computed from theory of elasticity by use of strain measurements taken from electrical resistance strain gages affixed to the specimens, Nos. 2, 11, and 13. Stress-strain curves are given in plates 1, 2, and 3. Specimens 2 and 11 were cycled at 10,000 psi; specimen 13 was cycled at 5000 psi. Results are given below.

Specimen No.	Modulus, psi x 10^6 Young's	Bulk	Shear	Shear Velocity, fps	Poisson's Ratio
		Dynamic Tests			
2	9.4	7.9	3.6	10,025	0.30
11	9.1	8.2	3.4	9,695	0.32
13	10.9	12.7	4.0	10,305	0.36
		Static Tests			
2	10.1	6.1	4.1	--	0.23
11	6.7	3.6	2.8	--	0.19
13	11.8	7.5	4.8	--	0.24

All of the rock tested herein is apparently rather rigid material, exhibiting little hysteresis. The slightly open nature of the hysteresis loops indicated small amounts of residual strain. The static moduli and static Poisson's ratios were computed from values taken from stress-strain curves at points corresponding to approximately 50 percent of the ultimate strength.

AD-A035 373 ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MISS F/G 8/7
TESTS OF ROCK CORES, DULUTH-VERMILLION STUDY AREA, MINNESOTA.(U)
JUN 70 R W CRISP, K L SAUCIER
UNCLASSIFIED WES-MP-C-70-9 NL

2 OF 2
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DATE
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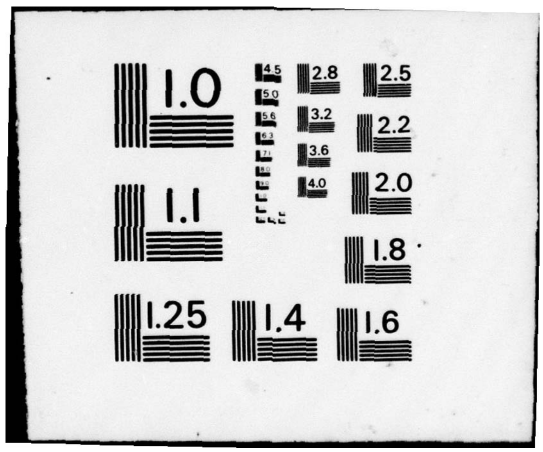

1.0
4.5
5.0
5.6
6.3
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

Conclusions

5. The core received from hole DV-CR-39 was identified by the field log received with the core as migmetite, gray to greenish-gray gneiss, and gray to pink granite. Physical test results varied somewhat, but generally showed rather good correlation with the nature of the discontinuities present in the specimen, i.e., critical-angle fractures, vertical or high-angle fractures, contacts, and bands. Generally, the specimens containing critical-angle fractures were the weakest, the group exhibiting an average compressive strength of 11,080 psi and failure usually occurring along the fractures. The specimens containing vertical or high-angle fractures exhibited the highest average compressive strength (24,640 psi), indicating that fracturing of this type had little if any effect on strength.

Property	Specimens with Contacts or Bands	Specimens with Vertical or High-Angle Fractures	Specimens with Critical-Angle Fractures
Specific Gravity	2.711	2.801	2.874
Schmidt Number	53.2	52.7	49.8
Compressive Strength, psi	16,980	24,640	11,080
Compressional Wave Velocity, fps	19,510	20,675	20,470
Young's Modulus, psi x 10^6	6.7	11.0	--

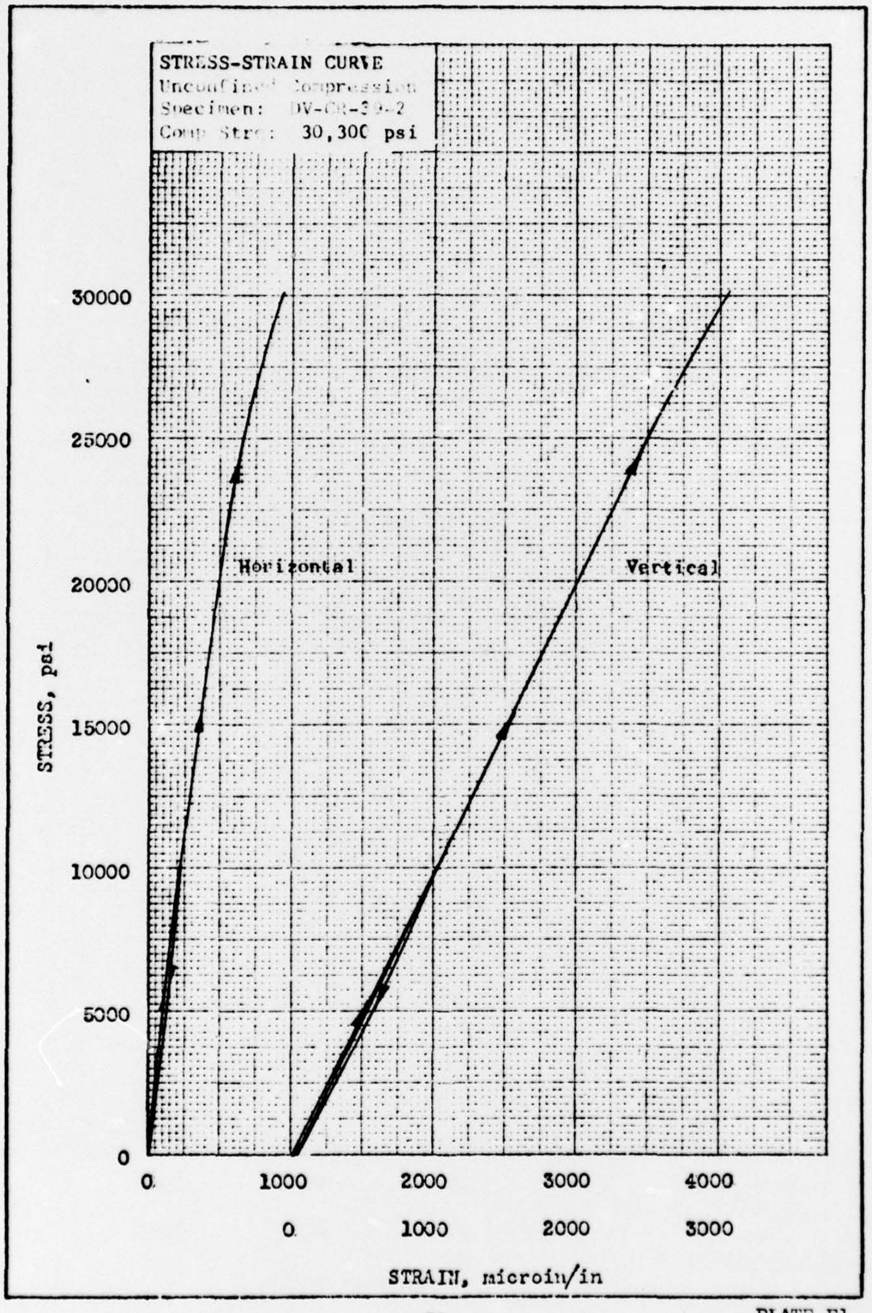

STRESS-STRAIN CURVE
Unconfined Compression
Specimen: DV-CR-39-2
Comp Str: 30,300 psi
Horizontal
Vertical
STRESS, psi
0
5000
10000
15000
20000
25000
30000
0 1000 2000 3000 4000
0 1000 2000 3000
STRAIN, microin/in

PLATE E1

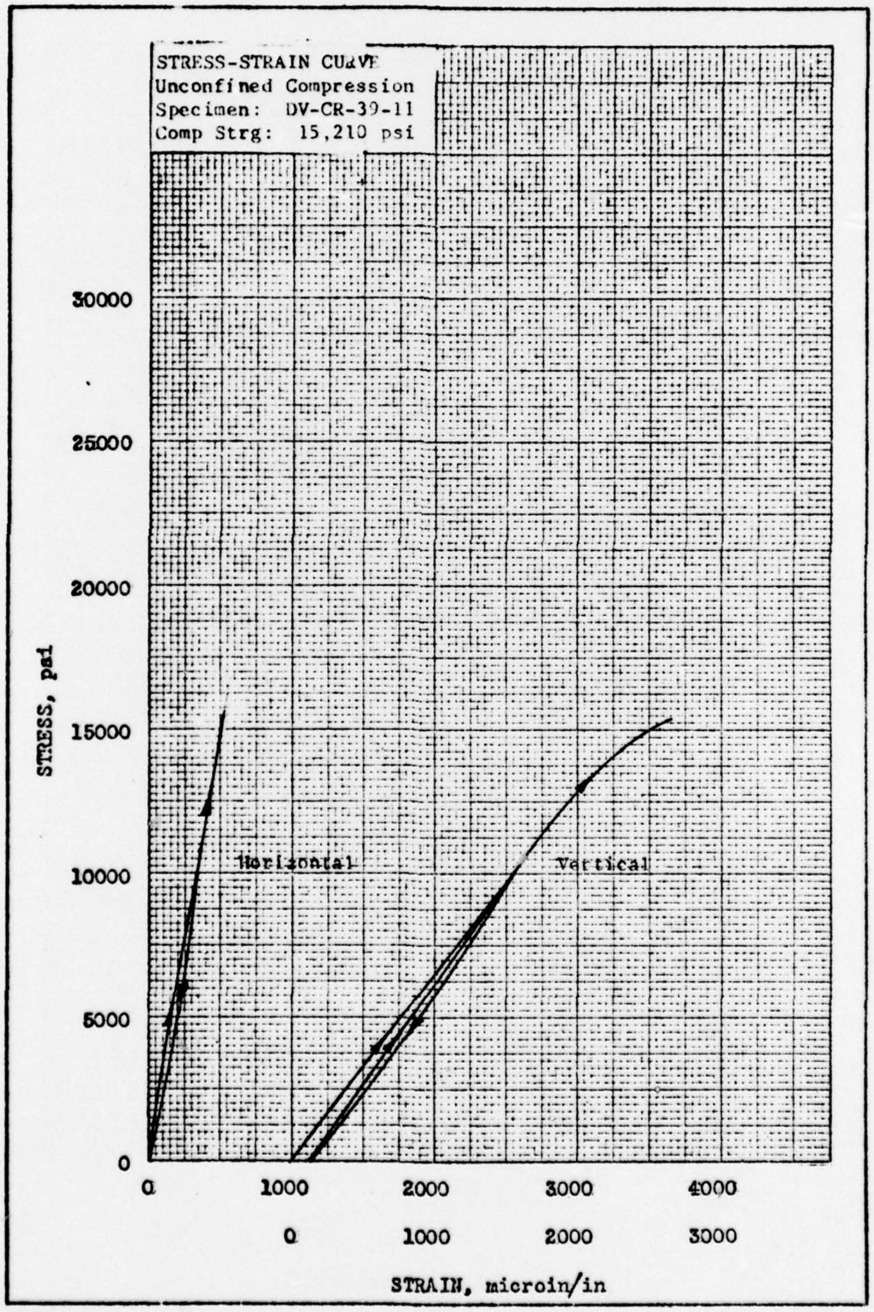
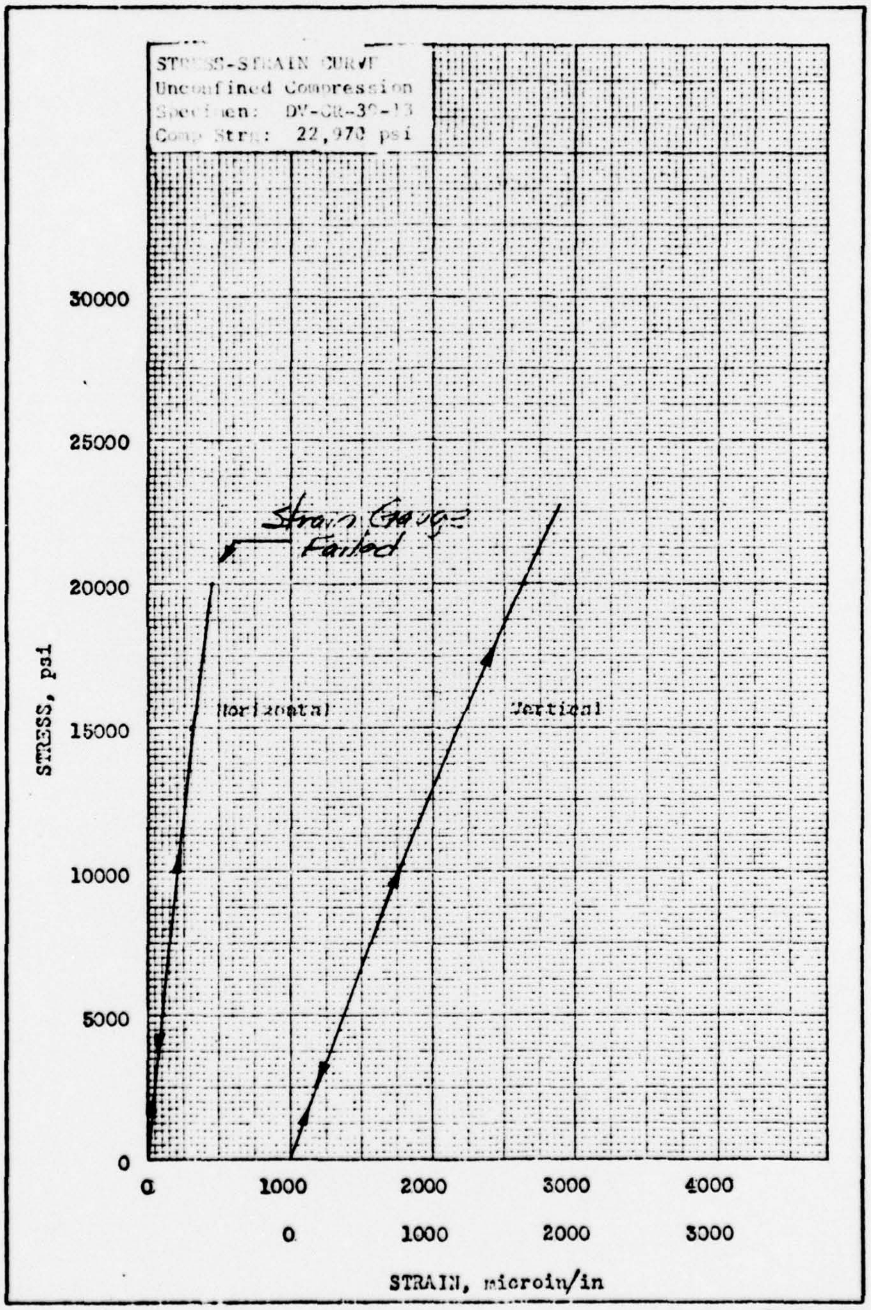

STRESS-STRAIN CURVE
Unconfined Compression
Specimen: DV-CR-39-11
Comp Strg: 15,210 psi
30000
25000
20000
15000
10000
5000
0
STRESS, psi
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
STRAIN, microin/in

PLATE E2


STRESS-STRAIN CURVE
Unconfined Compression
Specimen: DV-CR-30-13
Comp Strn: 22,970 psi
Strain Gauge Failed
Horizontal
Vertical
STRESS, psi
30000
25000
20000
15000
10000
5000
0
0
1000
2000
3000
4000
0
1000
2000
3000
STRAIN, microin/in

APPENDIX F

DATA REPORT

Hole DV-CR-40

3 October 1969

Hole Location: St. Louis County, Minnesota

Township 57N, Range 13W, Section 8

2558' W/EL, 792' N/SL, SE 1/4 SW 1/4

Longitude: 92° 00' 57.2"

Latitude: 47° 25' 55.6"

Core

1. The following core was received on 26 September 1969 for testing:

Core Piece No.	Approximate Depth, ft
1	7
2	18
3	29
4	38
5	48
6	58
7	68
8	74
9	79
10	88
11	97
12	108
13	115
14	125
15	134
16	143
17	153
18	163
19	172
20	181
21	192
22	199

Description

2. The samples received were quite uniform in appearance. According to the field log received with the core, the rock was identified as blue-gray gabbro. Specimen Nos. 1, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, and 21 contained fractures, most of which were tightly healed.

Quality and uniformity tests

3. To determine variations within the hole, specific gravity, Schmidt number, compressive strength, and compressional wave velocity were determined on specimens prepared from representative samples as given below:

	Sample No.	Description	Core Depth	Sp Gr	Schmidt No.*	Comp Strg, psi	Comp Wave Vel, fps
Medium-grained gabbro	2	Intact Rock	18	2.807	55.5	47,730	22,790
	3	Intact Rock	29	2.818	51.1	48,480	23,505
	4	High-Angle, Healed Fracture	38	2.799	51.6	17,420	23,235
	5	Intact Rock	48	2.801	--	50,580	23,180
	8	High-Angle, Healed Fracture	74	2.812	56.2	17,580	23,320
	12	**High Angle** ~~Critical-Angle~~, Healed Fracture	108	2.778	--	33,940	22,735
	13	High-Angle, Healed Fracture	115	2.803	52.9	34,850	23,350
	14	Intact Rock	125	2.810	53.7	57,880	23,390
	20	Critical-Angle, Healed Fracture	181	2.815	54.9	16,050	23,030
	21	High-Angle, Healed Fracture	192	2.800	--	32,270	23,290
Average of Intact Specimens (4)				2.809	53.4	51,170	23,220
Average of Fractured Specimens (6)				2.801	53.9	25,350	23,160

* Schmidt hammer test not conducted on several specimens due to possibility of breakage.

4. Of the several specimens tested containing healed fractures, Nos. 4, 8, and 20 failed at much lower stresses than the remainder of the specimens in the group. These lower ultimate strengths showed no correlation with angle of inclination of the respective fractures, indicating that the strength variation might rather have been the result of variation in the filler material or the tightness of the fractures. The specific gravity and compressional wave velocity results are indicative of a dense, uniform, competent rock.

Moduli of deformation

5. Representative specimens were selected for dynamic and static moduli of deformation tests. The dynamic moduli were determined by the proposed ASTM method for determination of ultrasonic pulse velocities and elastic constants of rock. The static moduli were computed from theory of elasticity by use of strain measurements taken from electrical resistance strain gages affixed to the specimens, Nos. 5, 12, and 21. Stress-strain curves are given in plates 1, 2, and 3. Specimens 12 and 21 were cycled at 10,000 psi; specimen 5 was cycled at 35,000 psi. Results are given below.

Specimen No.	Modulus, psi x 10^6 Young's	Bulk	Shear	Shear Velocity, fps	Poisson's Ratio
		Dynamic Tests			
5	12.1	14.3	4.5	10,910	0.36
12	11.2	13.8	4.1	10,505	0.36
21	11.8	14.7	4.4	10,740	0.36

(Continued)

(Continued)

Specimen No.	Modulus, psi x 10^6 Young's	Bulk	Shear	Shear Velocity, fps	Poisson's Ratio
		Static Tests			
5	14.1	10.7	5.5	--	0.28
12	13.9	10.7	5.4	--	0.28
21	14.7	9.8	5.9	--	0.25

All of the rock tested herein is apparently very rigid material, exhibiting little hysteresis. The erratic behavior of the stress-strain curves during the early phases of loading of specimen No. 21 was probably due to internal redistribution of stresses around the healed fracture. A high degree of uniformity of material from this hole is also indicated by the moduli results.

Conclusions

6. The core received from hole DV-CR-40 was identified as blue-gray gabbro by the field log received with the core. The core was very uniform in appearance; however, many specimens contained healed fractures. Physical test results indicated that the intact material was a very competent rock, exhibiting an average compressive strength of 51,170 psi. Even the fractured specimens yielded a minimum compressive strength of 16,000 psi and a compressional wave velocity of 23,000 fps.

Property	Intact Specimens	Fractured Specimens
Specific Gravity	2.809	2.801
Schmidt Number	53.4	53.9
Compressive Strength, psi	51,170	25,350
Compressional Wave Velocity, fps	23,220	23,160
Static Young's Modulus, psi x 10^6	14.1	14.3

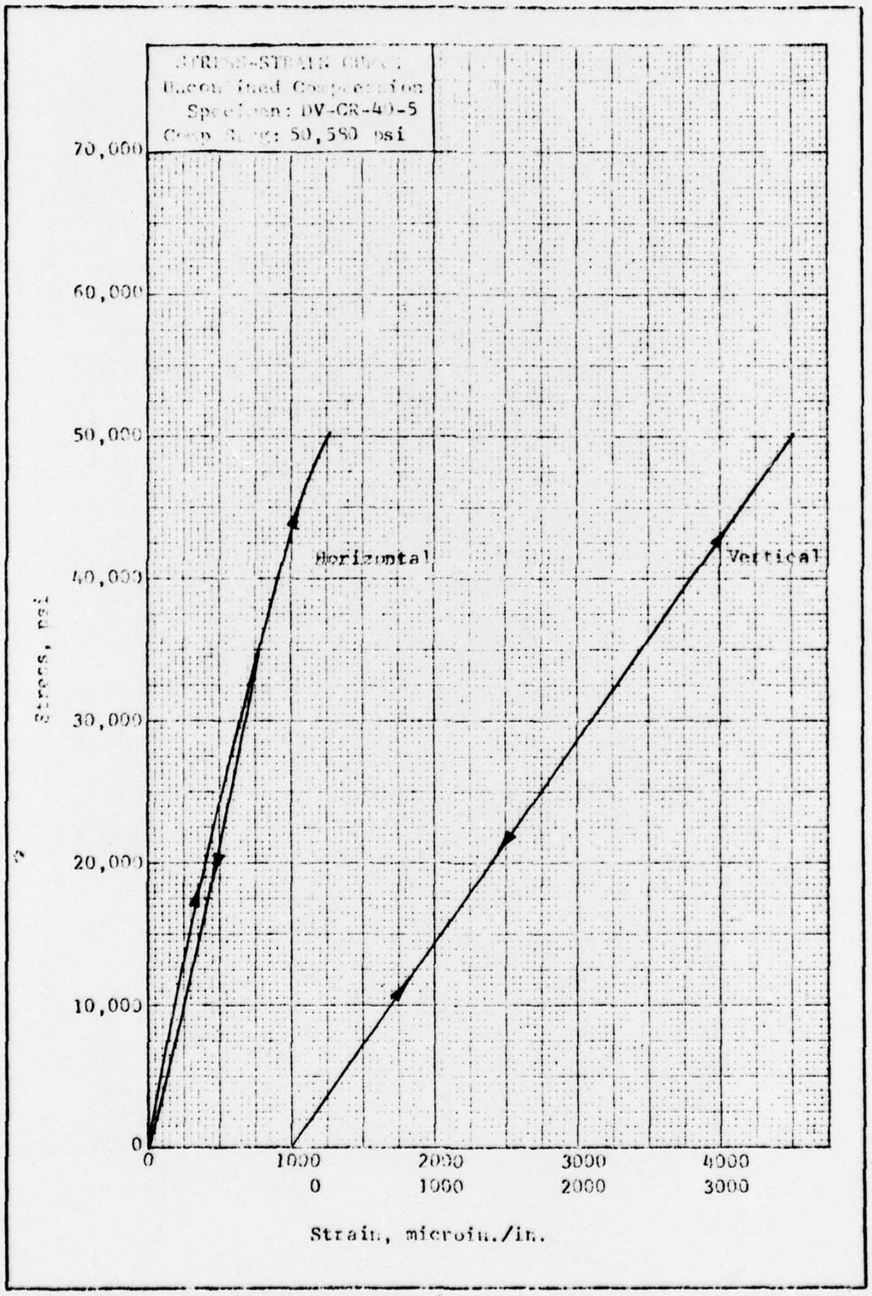

DV-CR-40-5
50,580 psi
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Stress, psi
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
Strain, microin./in.

PLATE F1

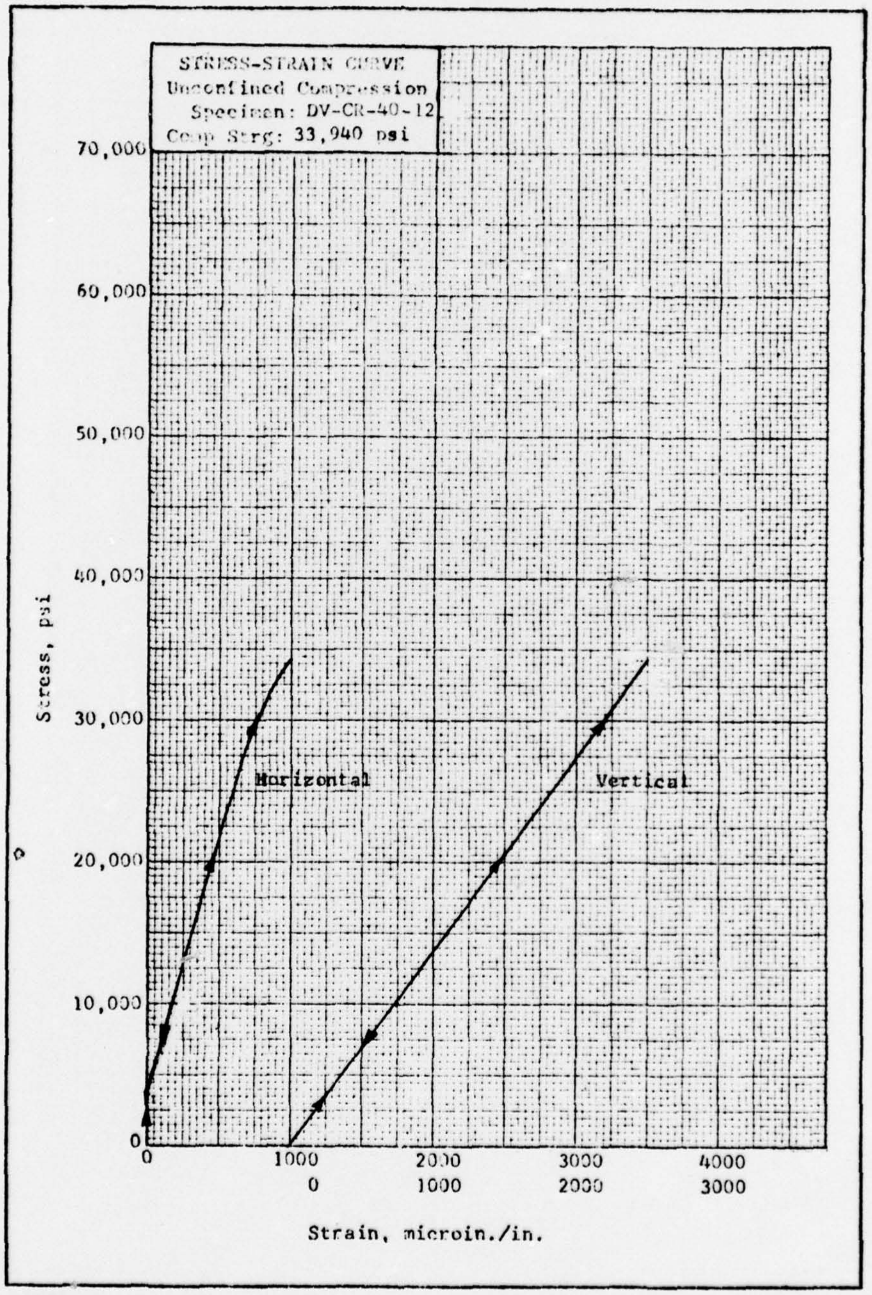
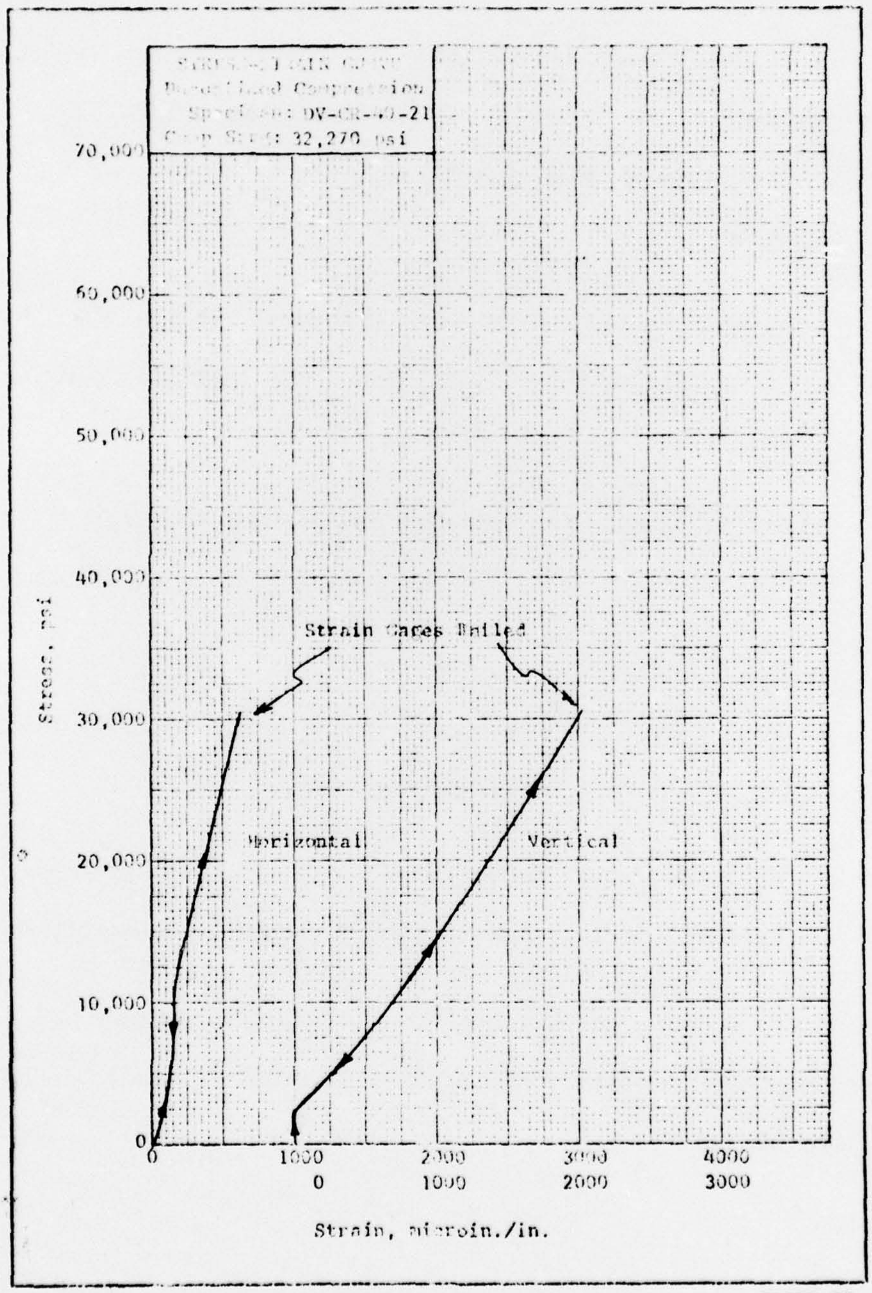

STRESS-STRAIN CURVE
Unconfined Compression
Specimen: DV-CR-40-12
Comp Strg: 33,940 psi
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Stress, psi
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000
Strain, microin./in.

PLATE F2



32,270 psi
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Horizontal
Vertical
0
1000
2000
3000
4000
0
1000
2000
3000

PLATE F3

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(9) Final report, Sep - Oct 69,

5. AUTHOR(S) (First name, middle initial, last name)

(10) Robert W./Crisp
Kenneth L./Saucier

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13. ABSTRACT

Laboratory tests were conducted on rock core samples received from six core holes in the Duluth-Vermillion study area of Koochiching, Lake, and St. Louis Counties, Minnesota. Results were used to determine the quality and uniformity of the rock to depths of 200 feet below ground surface. The rock core was petrographically identified as predominantly tonalite and gabbro, with relatively minor amounts of amphibolite, granite, and gneiss. Many specimens contained fractures ranging in orientation from vertical to horizontal. Several specimens contained bands and/or contacts with other types of rock. Evaluation on a hole-to-hole basis indicates the tonalite represented by specimens from Hole DV-CR-19 to be quite uniform and very competent. This material should offer very good possibilities as a competent hard rock medium. The tonalite, medium-grained gabbro, and granite and granitic gneiss representing Holes DV-CR-17, -40, and -9, respectively, exhibited physical properties typical of relatively competent to very competent material, and all should offer reasonably good possibilities as competent media. The coarse-grained gabbro from Hole DV-CR-24, and the amphibolite and tonalite from Hole DV-CR-39, were generally marginal (compressive strength 8,000-12,000 psi) to relatively competent (compressive strength >12,000 psi) in quality, with only one specimen (DV-CR-39, Specimen 7, an amphibolite) yielding an ultimate uniaxial compressive strength characteristic of incompetent rock. Evaluations have been confined to specimens from single holes and, therefore, more extensive investigation will be required in order to expand evaluations to entire areas of media.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Duluth-Vermillion study area, Minn.						
Petrographic examination						
Rock cores						
Rock properties						
Rock tests						